MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Naval Architecture and Marine Engineering

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COMPUTER APPLICATIONS TO THE STRUCTURAL DESIGN OF A COMBINATION FRAMED MIDSHIP SECTION

(VOLUME 1)

by

CHARLES EDWARD ROTH, 111
DONALD LIU

January, 1966

This work was performed in part under
Contract Nonr 3962 (11) (X) administered by the
David Taylor Model Basin

Cambridge, Massachusetts

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ABSTRACT

This computer program for the design of a midship section is derived from the structural midshipsection synthesis of a Naval destroyer by Pramud Rawat, and is based upon work by Ralph Davis (5) and Manley St. Denis (17). The logic of cycling from a set of arbitrarily selected initial thicknesses, to an optimum closed solution for least weight was originated in the destroyer design, and has been used as a basic premise in the formulation of this program. Any arrangement of transverse or longitudinal framing systems with all practical combinations of decks and longitudinal bulkheads is now included within the scope of the design.

The current program is formulated under merchant ship criteria as defined by the American Bureau of Shipping derived in Refs. (8) and (12). Substitution of Naval standards, or any other, is easily done. Presently, the structural design is restricted to the midsection of a mild steel ship with a simple hull geometry. The program is intended as a framework for the design of any realistic ship composed of any structural material; therefore, every attempt has been made to make the logical design process general enough so that expansion can be made in several directions without extensive revision of either the theory, or the computer program. Since the program has reached the limits of the IBM 7094 computer at the M.I.T. Computation Center, requiring several storage tapes and a long running time,

enlargement of the scope must be accomplished by splitting the overall program into separate units which may be calculated in successive stages. Use of the IBM system 360 computer would alleviate the current difficulties with program size.

ACKNOWLEDGMENT

Throughout this synthesis, the authors have continually relied upon previous work in the field of rational ship structural analysis. The basic techniques were initiated by Professor J. Harvey Evans; and all related developments at M.I.T., including this design, have been under his guiding hand. His advice has been of great help in formulating many of the decisions herein. This work is an extension of a concept devised by Pramud Rawat to whom the authors are also indebted.

All computer calculations were performed at the M.I.T. Computation Center.

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LIST OF SYMBOLS

The general nomenclature is given below. Symbols with meanings other than the one designated below are specifically defined in the text. Subscripts are also defined where used within the text.

a	transverse frame spacing, ft.
α	angle used to define location of structural members on the bilge turn
AC	area constant for plates, in.
A_t	area of total cross section, sq. in.
B	breadth of ship, ft.
β	angle used to define location of structural members on bilge turn
BM	bending moment imposed upon ship, tons-ft.
c	camber of main deck, ft.; and a locally defined constant
C_b	block coefficient
d	deadrise, ft.
D	depth of ship to strength deck, ft.
E	Young's modulus, psi
F	longitudinal frame spacing, ft.
h	water head, ft.
H	full load draft, ft.
i	subscripting index designating structural members
IC	inertia constant for plates, in x sq. ft.

I_t total inertia of cross section about base line, sq. in. x sq. ft.

j index defining structural members

k radius of gyration, in.

K non-dimensional coefficient

L spacing of webs and length of sections, ft.

M bending moment on composite plate-stiffener beam, in-lbs.

M_t area moment of total cross section about base line, sq. in. x ft.

N number of plates, or stiffeners in a section

P compressive load on a member, lbs.

ϕ angle of deadrise

q normal loading on composite beam, lbs/ft.

R bilge radius, ft.

S_1 primary bending stress, psi

S_2 secondary girder stress, psi

S_3 tertiary plate bending stress, psi

S_{cr} critical buckling stress, psi

S_L limiting primary stress, psi

S_Y yield strength in tension or compression, psi

u Poisson's ratio

V function of magnification factor used in Timoshenko formula

w weighting function used when refining plate thickness

W plate width, ft.

x	horizontal coordinate of a structural element, ft.
y	vertical coordinate of a structural element, ft.
Z	section modulus of plate-stiffener combination, cu. in.
Z_{abs}	section modulus of composite beam specified by American Bureau of Shipping, cu. in.
Z_L	section modulus of total midship cross section required by Load Line Regulations, ft. x sq. in.
Z_T	section modulus required by Timoshenko formula for composite beam, cu. in.

CHAPTER I

INTRODUCTION

This design synthesis is intended as a means for studying structural characteristics of the longitudinally continuous material at a ship midsection. Presently, the design is aimed at satisfaction of merchant ship criteria, but the general theory is applicable to ships designed under either Naval or Merchant standards. The program is organized so that formulations and design criteria can easily be modified without disturbing the basic philosophy.

Since the program is for preliminary design, no attempt is made to rigorously satisfy all specific details in the design process. A logical approach is evolved, based upon elementary structural principles; which yields scantlings capable of resisting loadings expected to be imposed upon any ship under study. The loadings and hull geometry are first defined, and then enough structural material is provided to just satisfy the governing design criteria. Therefore, the resulting structure is optimized upon a least weight basis.

The applications of a computer to ship structural design is used most advantageously in a process involving iteration for creating an optimum structural design. Therefore, each step of this design process is a building block in an iterative procedure.

Principal dimensions for the ship are initially selected and from these parameters a coordinate system for the longitudinally continuous material at the midship section is determined. Then the scantlings of the longitudinal continuous members are calculated so as to meet given stress requirements. These scantlings are refined so that a minimum weight solution is attained which satisfies all strength requirements. Each refinement is considered as a complete design cycle, which will be referred to by number, e.g. "Cycle 1".

Cycle 1 begins with a set of scantlings; changes them according to certain stress criteria, and then displays the results. At the beginning of the cycle, the initial set of scantlings undergoes change, where yielding under lateral load is the governing criteria. Then the cycle divides into two branches or sub-cycles which will be designated as Cycles A and B. Using the scantlings determined under lateral load, Cycle A attempts to satisfy the limiting primary bending stress on the hull girder by increasing the thicknesses of those plates located farthest from the ship neutral axis. Using the same initial scantlings as Cycle A, Cycle B also attempts to satisfy the primary bending stress except that the plating thicknesses which are increased are those that buckle under the compressive primary stresses. At the conclusion of both cycles A and B, the scantlings are examined for deficiency in buckling strength. If the limiting primary stress is satisfied with plates that still buckle, the thicknesses of these plates are increased until buckling strength is satisfactory.

The results of both cycles A and B are displayed and a decision is made: either another complete design cycle is to be initiated using the scantlings of Cycle A or Cycle B, or the design cycle is terminated with the scantlings of Cycle A or Cycle B.

SCHEMATIC REPRESENTATION OF DESIGN PROCESS

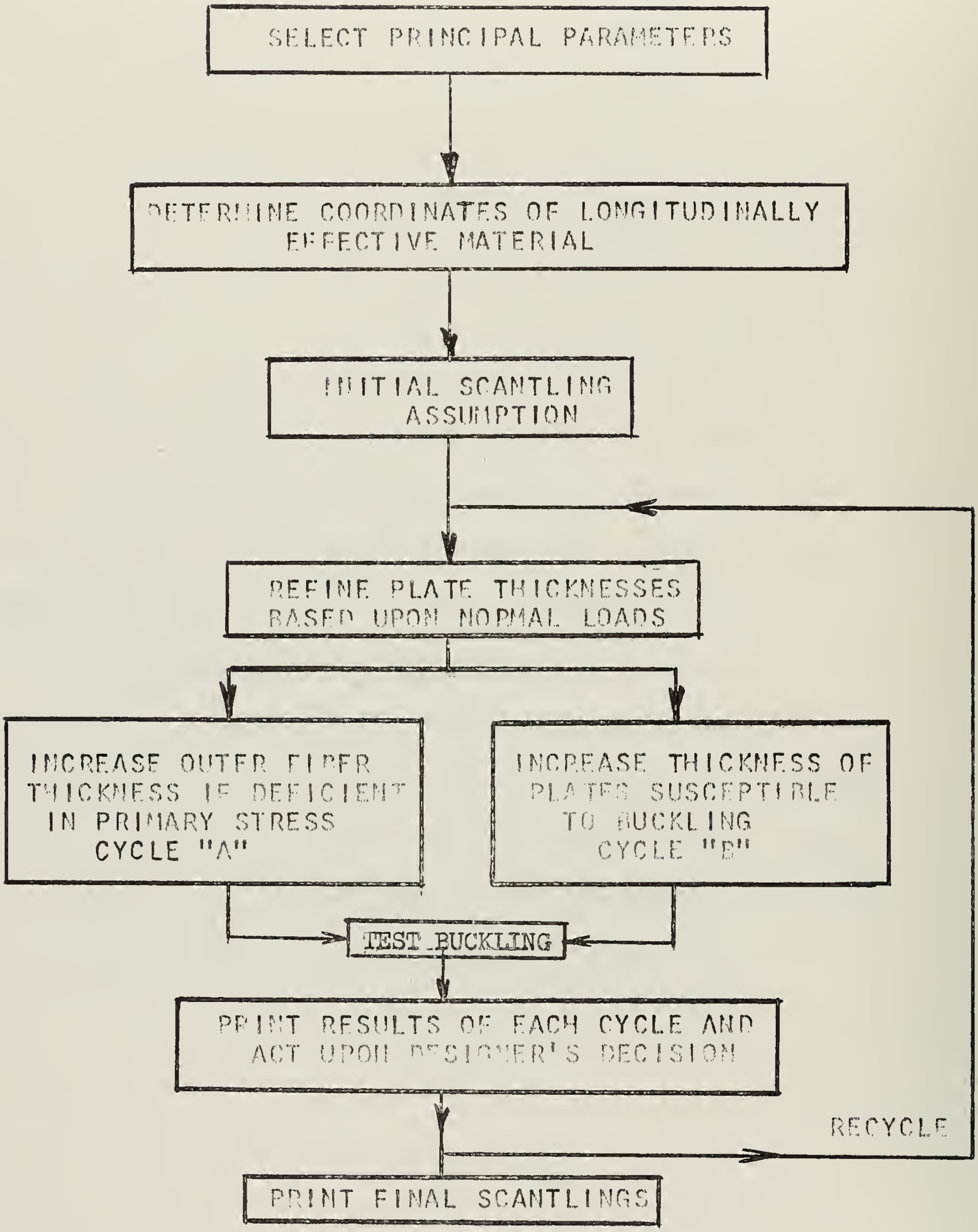


FIG. 1

CHAPTER II

BASIC PARAMETERS

The design synthesis begins with the selection of basic governing parameters. The geometric parameters define the hull geometry, the number of decks, bulkheads, and the type of framing system to be used within the sections formed by the shell, decks and bulkheads. Structural parameters such as limiting primary stress and bending moment can be calculated from the geometric properties of the ship or stated explicitly as initial criteria. Two equations used as the governing stress relationships to fulfill the physical strength of the material are:

$$(S_1)_i + (S_2)_i + (S_3)_i = (S_y)_i \tag{1}$$

and

$$(S_1)_{max} \leq S_L \tag{2}$$

where:

$(S_1)_i$ = ship bending stress

$(S_2)_i$ = girder bending stress

$(S_3)_i$ = plate bending stress

$(S_Y)_i$ = yield stress

S_L = limiting primary stress

i = the plate number index

In addition, the primary stresses must not subject the material to buckling failure. The standards to which the ship is being designed determine the manner in which S_L is defined. In naval practice, the limiting stress and bending moment are given structural parameters. In merchant ship design, which this synthesis deals with, a restriction is placed upon the midship section modulus as given by the Load Line Regulations. To determine the limiting stress, the bending moment has been estimated by the relationship:

$$BM = \frac{L^2 \cdot H \cdot B \cdot C_b}{35^2} \tag{3}$$

BM = bending moment, ft-tons

L = length between perpendiculars, ft.

H = draft, ft.

B = breadth, ft.

C_b = block coefficient

From Eq. 3, the limiting primary stress is:

$$S_L = \frac{BM}{Z_L} \tag{4}$$

where Z_L = required ship section modulus.

The value chosen for the bending moment is important to the design and should be a realistic value which is expected to be imposed upon the ship under worst conditions. The present estimation is generally accepted as reasonable, but may be changed as better formulations are developed. From Eq. 4, the limiting primary stress is directly related to the required section modulus, therefore, satisfaction of the stress requirements implies satisfaction of the structural requirements.

CHAPTER III

GEOMETRY OF THE MIDSHIP SECTION

The development of the midship section geometry is the first step in the design sequence. In order to facilitate the determination of a general realistic coordinate system, the basic hull shape was kept simple. The shell is assumed to have a flat bottom, perhaps with deadrise; vertical sides; a parabolic main deck. The other decks are flat and the possibility exists for inclusion of an inner bottom.

Stiffeners

Having selected the parameters for the hull geometry, the frame spacing for longitudinally framed sections must be determined. The cross section is considered as being divided into individual sections which are treated independently. These sections are the decks and inner bottom, the bulkheads, and the shell sections defined by the deck and inner bottom locations. Figure 2 depicts the arrangement of a typical cross section.

From the nominal frame spacing, the actual frame spacing for each section can be calculated. First, the number of stiffeners are determined for each section based upon the desired nominal spacing.

$$N_i = \frac{\int_{i\partial} (L)}{F_N} \qquad (5)$$

Where;

N_i = the integer number defining the number of stiffeners in section i

L = the length of any section

F_N = nominal frame spacing

i = any section (A through H in Figure 2)

Then the actual frame spacing for each section is found.

$$F_i = \frac{\int_i \partial(L)}{N_i} \tag{6}$$

where;

F_i = actual frame spacing of section i

The actual stiffener spacing has been calculated to be as near as possible to, but less than, the nominal.

When the frame spacing has been fixed, the coordinates for all longitudinals are calculated. The base line will define the X axis, while the center line will be the Y axis. The mathematical and graphical representations are shown below and in Figure 2.

<u>Section A</u>

$$A = L_a = \int_a \partial(L) = \int_{a1} \partial(L) + \int_{a2} \partial(L) = A1 + A2 \tag{7}$$

For A1; (on the flat bottom)

$$X_{aj} = j \cdot F_a \cdot \cos \Phi \tag{8}$$

$$Y_{aj} = j \cdot F_a \cdot \sin \Phi \tag{9}$$

$$\Phi = 2 \cdot d/_B \tag{10}$$

TYPICAL MIDSHIP SECTION

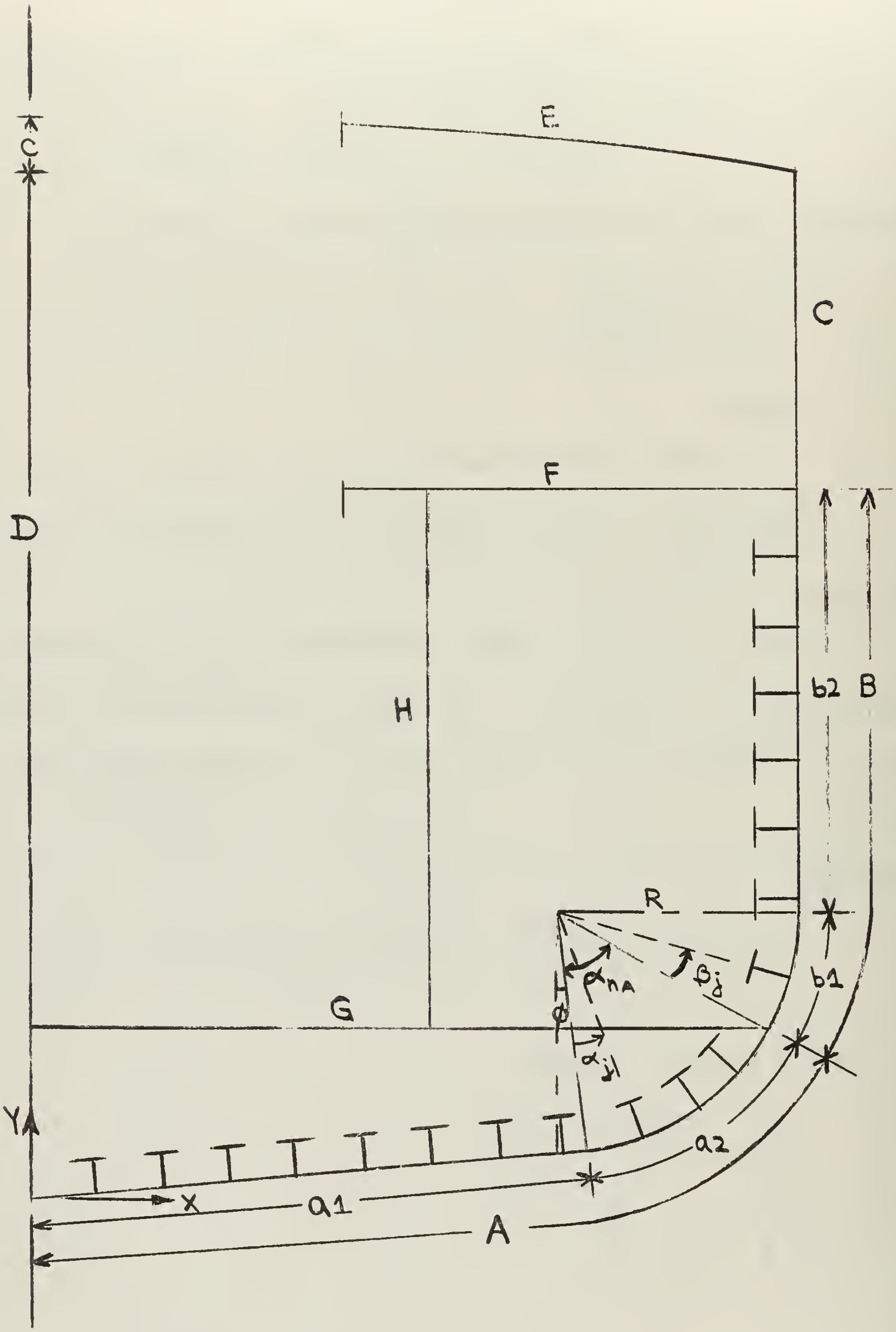


FIG. 2

where,

B = breadth

d = dead rise

j = number of jth longitudinal in the section ($j = 1,2,3, \ldots N_{a1}$)

X = horizontal coordinate

Y = vertical coordinate

For A2; (on bilge turn, below inner bottom) when $j = N_{a1} + 1$,

$$\alpha_j = \frac{F_a - \left[\int_{a1} \partial(L) - N_{a1} \cdot F_a\right]}{R} \tag{11}$$

R = bilge radius

when $j = (N_{a1} + 2), (N_{a1} + 3), \ldots N_A$

$$\alpha_j = \left[j - (N_{a1} + 1)\right] F_a/R \tag{12}$$

Therefore,

$$X_{aj} = B/_2 + R\cdot(\sin \alpha_j + \sin \Phi - 1) \tag{13}$$

$$Y_{aj} = R\cdot(1 - \cos \alpha_j) + d \tag{14}$$

<u>Section B</u>

$$B = L_b = \int_{b1} \partial(L) + \int_{b2} \partial(L) = B1 + B2 \tag{15}$$

For B1: (on bilge turn above inner bottom)

when $j = 1$

$$B_j = \frac{F_b - \left[\int_{b1} \partial(L) - N_a \cdot F_a\right]}{R} \tag{16}$$

when $j = 2,3, \ldots N_{b1}$

$$\beta_j = j \cdot F_B/R \tag{17}$$

Therefore,

$$X_{bj} = B/2 + R\left[(\sin(\Phi + \alpha_{na}) - 1 + \sin(\beta_j + \Phi + \alpha_{na})\right] \tag{18}$$

$$Y_{bj} = d - R\cdot\left[\cos(\beta_j + \Phi + \alpha_{na}) - 1\right] \tag{19}$$

where α_{NA} = total angle (see Figure 2)

For B2:(on vertical side above turn of bilge up to end of Section B)

$$X_{bj} = B/2 \tag{20}$$

$$Y_{bj} = (j - N_{b1})\, F_B - R\left[\cos(\beta_j + \Phi + \alpha_{Na})\right] + R + D \tag{21}$$

where $j = (N_{b1} + 1), (N_{b2} + 2), \ldots N_b$

<u>Section C</u> (all 'tween deck portions of shell side are similar)

$$X_{cj} = B/2$$

$$Y_{cj} = Y_{b,N_b} + F_B + (j \cdot F_c) \tag{22}$$

<u>Section E</u> (Parabolic main deck)

The general formula for a parabola is:

$$Y_e = KX_e^2 + b \tag{24}$$

At $X_e = 0$;

$Y_e = D + C$

where

D = depth of ship

c = camber

therefore,

$$b = D + C$$

At $Y_e = D$

$$X_e = B/2$$

and therefore,

$$K = {}^{-4\,c}/_{B^2}$$

Hence;

$$X_{ej} = j \cdot F_e \tag{25}$$

$$X_{ej} = D + c - 4c \cdot X_{ej}/B^2$$

$$j = 1,2,3, \ldots N_e \tag{26}$$

<u>Section F</u> (all 'tween decks are similar)

$$X_{fj} = j \cdot F_b \tag{27}$$

$$Y_{bj} = (\text{Depth}) - L_d \tag{28}$$

$$j = 1,2,3, \ldots N_F$$

<u>Section G</u> (inner bottom)

$$X_{gj} = j \cdot F_A \text{ when } X_{gj} \leq (B/2 - F_A) \tag{29}$$

otherwise,

$$X_{gj} = \frac{B/_2 - F_a}{2}, \quad (X_{gj} > B/_2 - F_a) \tag{30}$$

Y_{gj} = height of center vertical keel, given by $D/_{10}$.

Section H (Bulkheads)

The X coordinate of all bulkheads is fixed as being the nearest longitudinal frame, at the bottom of the bulkhead, to the nominally given distance of the bulkhead from the center line. Therefore, the bulkhead intersects a frame to provide a solid foundation. The Y coordinate of the longitudinals are measured by:

$$Y_{hj} = D_K + F_H \cdot j \qquad (31)$$

where,

D_k = height of a section at the intersection of that section with the bottom of the bulkhead.

The sections defined above are typical of all possible divisions found on a standard cross section. Equations (27) and (29) show that the longitudinals on the inner bottom do not necessarily line up with the 'tween deck longitudinals, but are in line with the longitudinals on the flat bottom. This allows the struts to be vertical in the double bottom structure. Since the depth of the hold is large, any misalignment of frames will hardly affect structural efficiency. But the double bottom longitudinals must be aligned or strength will be greatly impaired.

The general form of the equations remain fixed even though the configuration of decks and bulkheads may be varied. Of course, in the computer program, all eventualities have been considered so that the general forms are detailed and adopted for any particular arrangement.

Plate Seam Location

Now that the stiffener coordinates have been fixed, the next step in the development is to determine the location of plating seams about the cross section. Since the width of plating to be used has been designated to vary with the size of ship constructed, a standard stock plating width varying with the vessel length is chosen as a nominal width on the midsection. Shipyard practice requires that longitudinals be located in advance of plating seams. Therefore, the stiffeners are set and the plate seams subjected to variation. The plan is to avoid any intersection of stiffener or section boundary with a plate seam. All seams resulting from the nominal plate width are examined and modified if less than three inch clearance is found. This tolerance is to prevent welding difficulties or metallurgical weaknesses. Since the design is presently for mild steel ships, standard welding procedure for this material can be practical under the clearances allowed, (i.e., the stiffeners will be fillet welded and the plates butted). At present, the plate widths as derived from the nominal value do not conform to standard catalogue sizes. Adjustment must be made in order that all widths, when modified, maintain a standard size. For convenience, widths for certain strakes are found directly from formulations which meet the ABS requirements,(9),(12). These are the top and sheer strakes, center strake, keel plate, and stringer strakes.

Other plate widths are found in a manner similar to the method used to find the frame spacing for each section.

The hull shell, sections A through C, is divided into plate strakes by:

$$N_{ac} = \frac{\int_a^c \partial(L) - W_r}{W_s} \qquad (32)$$

where N_{ac} = integral number of plates to be used for the shell other than those whose width has already been established.

W_s = nominal standard plate width

W_r = established plate (keel, sheer, and top strakes) widths.

The actual plate widths on the shell are found by:

$$W_{ac} = \frac{\int_a^c \partial(L) - W_r}{N_{ac}} \qquad (33)$$

where, W_{ac} = actual plate width

All deck plates are found by:

$$N_i = \frac{\int_i \partial(L) - W_r}{W_s} \qquad (34)$$

where

W_r = the stringer plate width

N_i = integral number defining number of plates on decks excepting the stringer plate

therefore,

$$W_i = \frac{\int_i \partial(L) - W_r}{N_i} \qquad (35)$$

where W_i = actual plate width of section

The inner bottom and bulkhead plating widths are found by the same formulas used for the deck plating except that $W_r = 0$.

The coordinates for all seams are found by the same formulations, equations (7) through (31), as were used for the stiffener coordinates. The only difference is that the plate width W_i is substituted for the frame spacing F_i. As the coordinates for each seam are found, the seam is checked for conflict with stiffeners and section boundries. Should conflict occur, the seam is changed by three inches as mentioned previously. In actual practice this interference scarcely happens, so that this small modification does not cause large fluctuations in plate widths.

Lateral Loadings

The pressure head acting on each plate seam and longitudinal can be calculated from considerations of the hull geometry. All pressure heads are defined as the maximum under either, a heel of 30°, upright under a wave crest, or a specified green sea height presently taken as 5.25 feet on the main deck. Lateral loadings on bulkheads are also defined to be the appropriate water loadings, depending upon location. The maximum pressure head acting on the tween decks and the inner-bottom is presently set as the height of the tween deck and lower hold, respectively. These values are primarily from references (9) and (12), and do not account for local normal loads such as machinery. The required thicknesses from these head values were found (Ref. (9) and (12)) to conform closely to A.B.S. practice.

The formulation used to find the maximum heads are:

For heeled condition;

$$h_i = \left[H - Y_i + X_i \cdot \sin 30^{\circ} \right] \cdot \cos 30^{\circ} \tag{36}$$

where,

H = draft

h_i = head under heeling on members

and under a wave crest,

$$h_i = .6 \cdot L_{bp}^{0.6} - Y_i \tag{37}$$

The minimum head allowed acting on the main deck has been set for the present at 5.25 ft.

Geometric Constants

Although the scantlings of the structural members are yet unknown, geometric constants which are functions only of the coordinate system can be determined. For example, the area, first moment, and moment of inertia for each plate can be expressed as a function of thickness and width. Since the thicknesses are discrete values for each plate, integration is confined to the width of each plate. Except for the bilge and main deck, all plates are plane, and because each plate is of uniform thickness:

$$\therefore AC_i = 2\int_i \partial(L) \tag{38}$$

where,

$$AC_i = \text{area constant for plate i.}$$

The values for the first moment constant, MC_i, and the inertia constant, IC_i, must be developed for every orientation of plating.

On the flat bottom,

$$MC_i = 2\left[X_i^2 - X_{i-1}^2\right]\cdot \sin\Phi \tag{39}$$

$$IC_i = \frac{2}{3}\left[X_i^3 - X_{i-1}^3\right]\cdot \sin^2\Phi \tag{40}$$

Equations (39) and (40) apply to plates on the inner bottom and 'tween decks if $\Phi = 0$.

For plates on the bilge turn,

$$MC_i = 2\cdot r\cdot R\cdot(\theta_i - \theta_{i-1}) + 2R^2\cdot(\cos\theta_i - \cos\theta_{i-1}) \tag{41}$$

$$IC_i = 2\,r^2\cdot R\cdot(\theta_i - \theta_{i-1}) + 4\,r\cdot R^2\cdot(\cos\theta_i - \cos\theta_{i-1}) + R^3\,(\theta_i - \theta_{i-1}) - \frac{R^3}{2}\cdot(\sin 2\theta_i - \sin 2\theta_{i-1}) \tag{42}$$

where θ and r are defined in Fig. 3. For plates of the side shell or on bulkheads,

$$MC_i = (y_i^2 - y_{i-1}^2) \tag{43}$$

$$IC_i = \frac{2}{3}\cdot(y_i^3 - y_{i-1}^3) \tag{44}$$

BILGE PLATE GEOMETRY

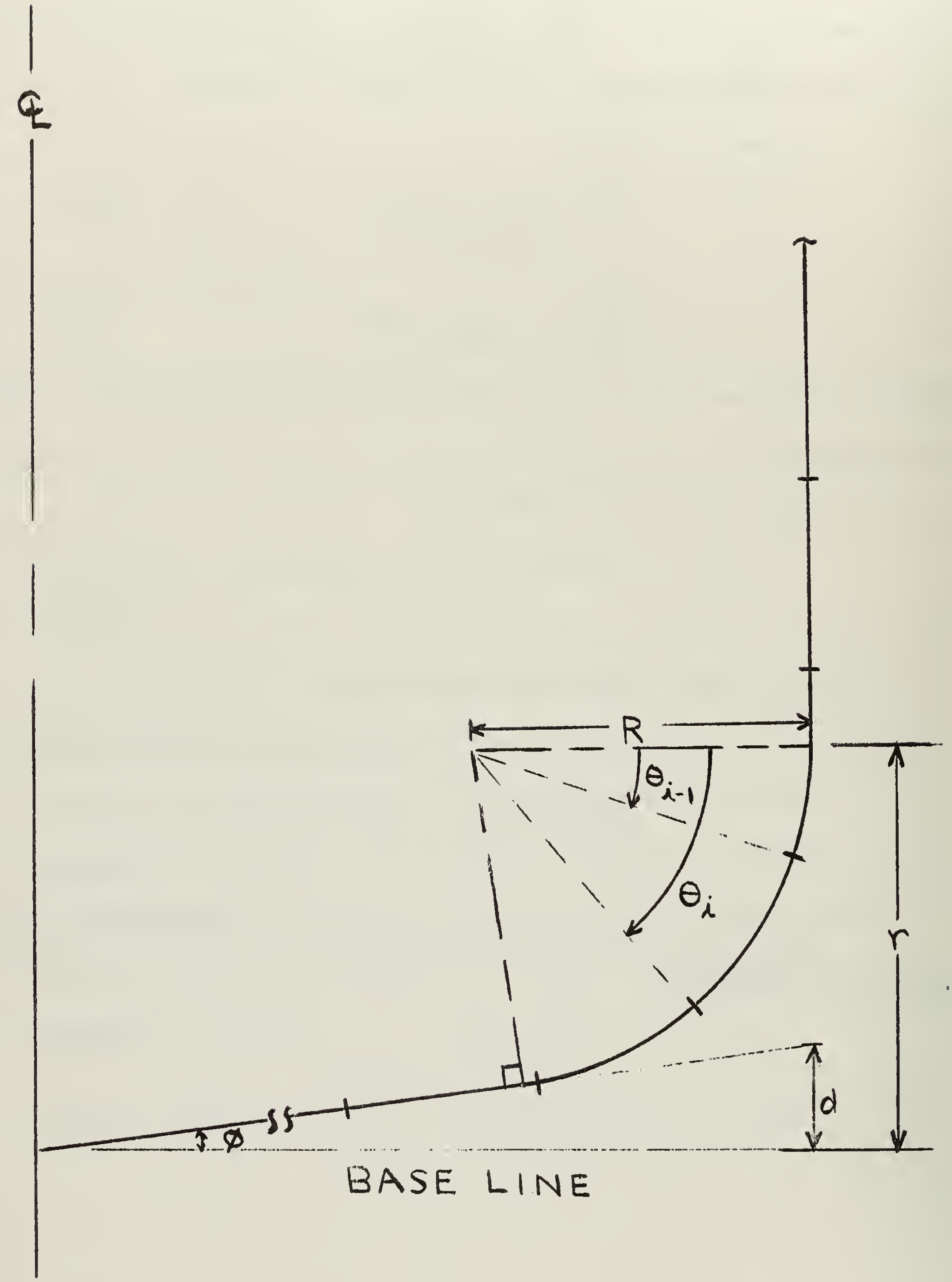


FIG. 3

The moment and inertia constants on the main deck are defined by:

$$MC_i = 2 \int_i \left(D + c - \frac{4c}{B^2} \cdot X_i^2\right) \cdot \left[1 + \frac{64c^2}{B^4}\right]^{1/2} \partial X \tag{45}$$

$$IC_i = 2 \int_i \left(D + c - \frac{4c}{B^2} \cdot X_i^2\right)^2 \cdot \left[1 + \frac{64c^2}{B^4}\right] \partial X \tag{46}$$

Equations (38) through (46) are given as double the actual value in order to account for the total ship.

The definition of a general coordinate system completes the first phase of the synthesis. Structural analysis has not yet been discussed and only geometric properties have been defined. No interaction occurs between calculation of the coordinates and the structural design synthesis. Therefore, geometry is fixed henceforth in the design and scantlings are determined based upon this fixed coordinate system.

CHAPTER IV

REFINEMENTS OF SCANTLINGS TO SATISFY NORMAL LOAD REQUIREMENTS

The first development of each complete design cycle is to refine the initial thicknesses, which are chosen arbitrarily, for satisfaction of normal loading under a stress schedule governed by Eq. (1). For each succeeding cycle, the initial thicknesses are those from either Cycle A or Cycle B of the previous design cycle. Proof that the choice of initial scantlings does not influence the final solution is given in Chapter VII.

As shown in Fig. 4, the sequence of refinement begins with the calculation of the geometric properties, (width, area, moment of inertia, etc.) associated with the initial thicknesses. Based upon these properties, S_1 is found. Then S_2 and S_3 are determined from Eq. (1). Thereafter, the stiffener scantlings are calculated in association with the plating thicknesses under the current stress schedule. Next, the existing plate scantlings are changed slightly in an attempt to meet the normal loading to be allowed by the current stress schedule. The new set of thicknesses determine a new stress schedule which will be the governing criteria for a further change in the plate thicknesses. This iterative procedure continues until the thicknesses developed do not change the stress schedule.

SCANTLING REFINEMENT BASED UPON NORMAL LOADING

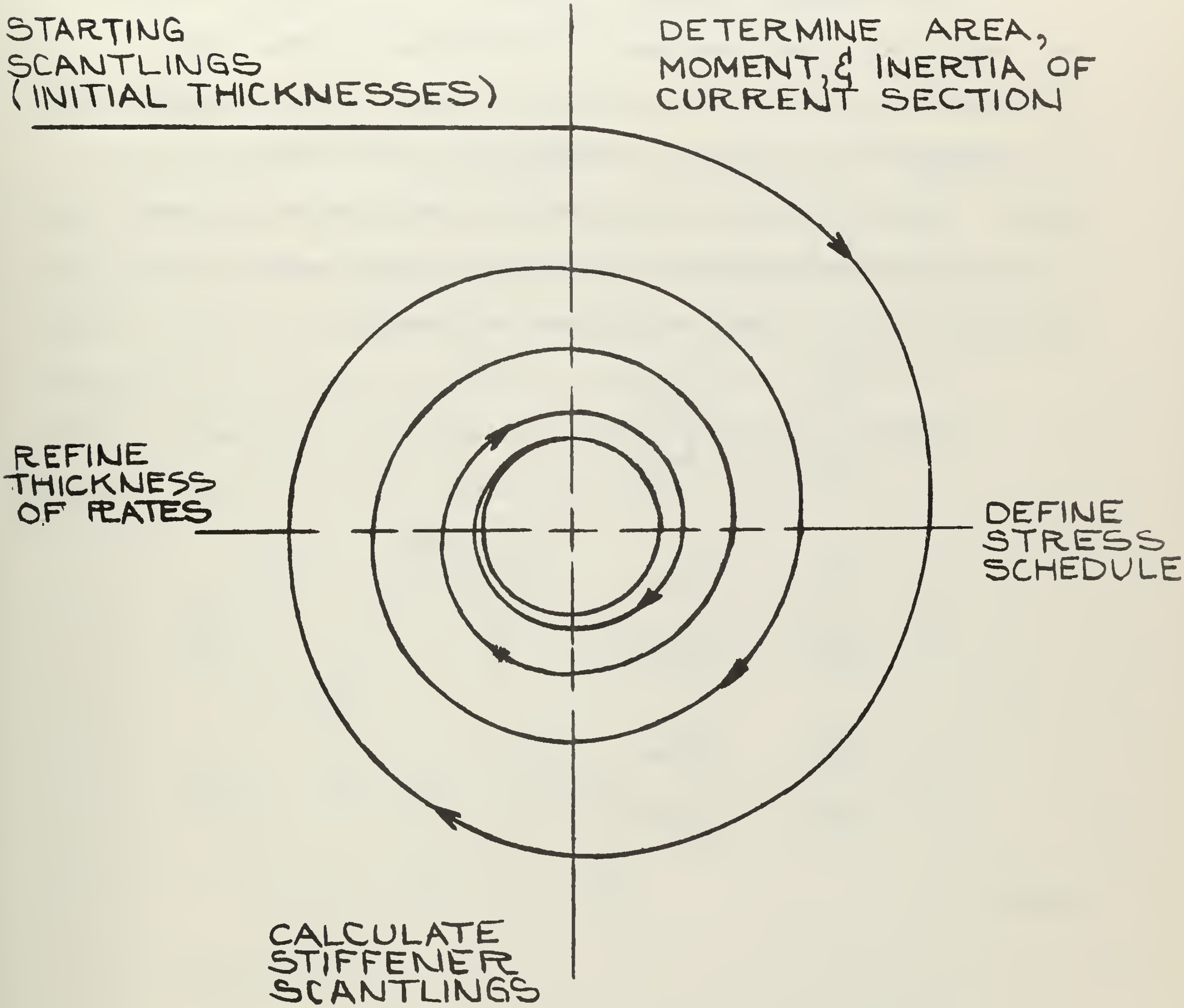


FIG. 4

Geometric Properties of the Plates

The geometric constants, independent of the plate scantlings were calculated in the development of the coordinate system. The thicknesses of each plate are multiplied by these constants to give the individual areas, moments and inertias about the baseline for each member. These properties, together with the same geometric properties of the longitudinal stiffeners, yield the total areas, moments, and inertias of the hull cross section about the baseline:

$$A_t = \sum_{i=1}^{TP} A_i + \sum_{j=1}^{TL} A_j \qquad (47)$$

$$M_t = \sum_{i=1}^{TP} M_i + \sum_{j=1}^{TL} M_j \qquad (48)$$

$$I_t = \sum_{i=1}^{TP} I_i + \sum_{j=1}^{TL} I_j \qquad (49)$$

where:

$A_i = AC_i \cdot T_i$

$M_i = MC_i \cdot T_i$

$I_i = IC_i \cdot T_i$

TL = Total No. of Longitudinals

TP = Total No. of Plates

T_i = thickness of plating

A_t = cross sectional area of total midship section

M_t = area moment of total about baseline

I_t = moment of inertia of cross sectional area of total about baseline

Stress Schedule

As assumed throughout the design, the ship acts like a simple beam in bending, therefore basic flexural formulas are used in the development of the relationship between the bending stress and the imposed bending moment. Since the coordinate system is developed with the baseline as an axis, the stress is found with the base line as a reference. This avoids the necessity of depending upon a constantly changing neutral axis in the stress calculation. See Fig. 5.

$$(S_1)_i = \left| \frac{BM \cdot C_i}{I_o} \right|$$

where:

$$y_o = \frac{M_t}{A_t}$$

$$C_i = \left| y_o - y_i \right| = \left| \frac{M_t}{A_t} - y_i \right|$$

$$I_o = I_T - A_t \cdot y_o^2 = I_T - \frac{M_t^2}{A_t}$$

Therefore,

$$(S_1)_i = \left| \frac{M_t - A_t \cdot y_i}{A_t \cdot I - M_t^2} \right| \cdot BM \qquad (50)$$

INDIRECT SOLUTION FOR PRIMARY STRESS

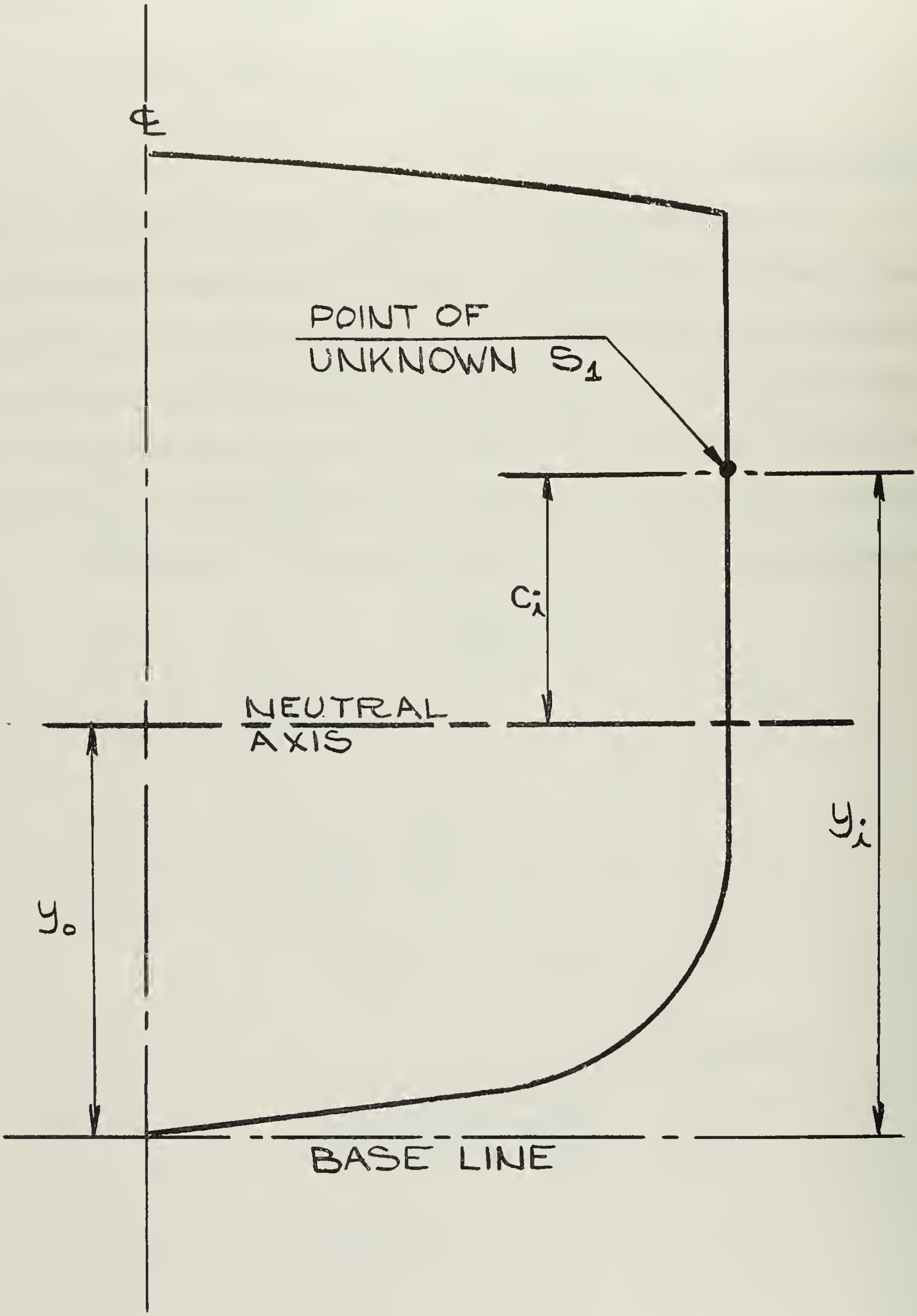


FIG. 5

Thus, given the vertical height of a structural member above the base line, the primary stress acting on the member is found from Eq. (50).

Calculation of Longitudinal Stiffener Scantlings

As seen in Fig. 4, the values of stiffener scantlings lag behind the plate thicknesses after each refinement. This is because the stiffeners are associated with plate thicknesses found under a stress schedule which is one step behind the current refined thicknesses. From the nature of the iteration, one step must always lag behind the others, therefore the least harmful effect was chosen. The stiffeners amount to approximately 20% of the cross sectional area of the plating, thus if the scantlings are not current, the effect on the stress schedule as reflected through the area, moment, and inertia, is small. As the plate thicknesses are further refined, causing a convergence on a constant stress schedule, the stiffener scantlings become updated and finally match the plate thicknesses.

In the design of stiffeners for the longitudinally framed sections, the scantlings must be of sufficient size so that the section modulus of the stiffener effective plate combination is equal to, or greater than the section modulus required by instability and yielding criteria. St. Denis Ref. (17), states that:

$$S_1 + S_2 \leq S_y/1.25$$

therefore, the maximum girder stress becomes;

$$S_2 = S_y/1.25 - S_1 \qquad (51)$$

To calculate the required stiffener scantlings, the longitudinal is assumed clamped at its ends because of structural continuity. The effective plating width is assumed equal to the minimum of: one frame space, or 60 times the thickness of plating.

The geometric properties of the stiffeners used in the composite beam are derived from the properties of a basic stiffener. The required stiffener is determined by a proportionality constant which is simply a scale factor and is related to the basic stiffener as shown in Fig. 6. The proportionality constant must vary the basic stiffener scantlings so that the composite beam has the required section modulus. As seen in Fig. 6, the proportionality constant can not be expressed as a direct function of the section modulus. The effective plating width is selected to be used in combination with several proportionality constants, and using constants ranging from 0.3 to 6.6 the properties are plotted against the resulting composite section modulus. Then, by LaGrangian Interpolation Ref. (11), the required section modulus may be used to determine the necessary proportionality constant. The basic stiffener for the present, is a structural - T, cut from a WF - I, and is of sufficient size so that all possible ranges may be conveniently handled. Once a proportionality constant has been determined, any geometric property of the required section is related to the basic stiffener by this constant.

To determine the required section modulus, the longitudinal is assumed to act as a beam-column member. Timoshenko's formula,

PLATE STIFFENER RELATIONSHIP

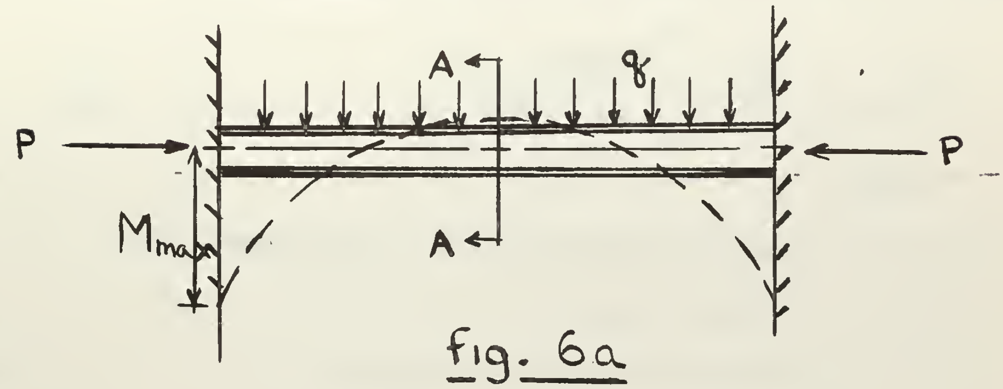
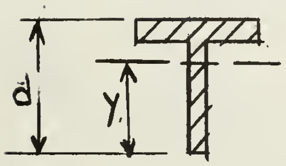
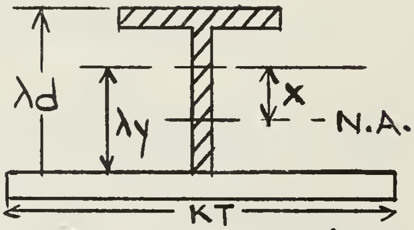


fig. 6a



BASIC T-SECTION

fig. 6c



SECTION A-A

fig. 6b

$$Z = \frac{\lambda^4 I_o + A\lambda^2 x^2 + Kt^2(\frac{t}{2} + y - x)^2}{d - y + x}$$

where:

d = depth of basic section

Z = section modulus of the plate-stiffener combination required

A = area of basic section

Kt = effective width of plating

I_o = moment of inertia of basic section about own axis

λ = proportionality constant

y = distance of neutral axis from toe of basic section

t = thickness of plating

$$x = \frac{Kt^2(\lambda y + \frac{t}{2})}{\lambda^2 A + Kt^2}$$ = shift of neutral due to plate addition

FIG. 6

Ref. (18), for a clamped beam under combined lateral and axial loads is used to calculate the required section modulus.

$$M_{max} = \frac{qL^2}{12} \cdot \left[\frac{3(\tan V - V)}{V^2 \tan V} \right] \qquad (52)$$

where,

M = maximum bending moment of the beam at the clamped ends

q = normal load per unit length

L = length of beam

$$V = \sqrt{PL^2/4EI} = L/k \sqrt{S_1/4E}$$

and,

P = compression loading

k = radius of gyration

E = Young's modulus

Using the above relationships, and the basic relationship between bending moment and section modulus,

$$Z_T = \frac{qL^2}{12\, S_2} \cdot \left[3 \frac{\tan V - V}{V^2 \cdot \tan V} \right] \qquad (53)$$

where

Z_T = required section modulus from Timoshenko formula

Equation (53) is seen to be comprised of two parts, the standard normal loading and a magnification factor. The first is the result of only the water head or any of the normal loads on the beam. The second factor indicates the amount that the normal loading is magnified due to compressive stresses acting on the beam. Rather than define the two effects separately, the single section modulus is a result of compounding the normal load with an indicator reflecting the magnitude of the compressive stress. Therefore, since both axial and bending stresses are either known or set, a section modulus may be determined.

When the actual compressive load is small in comparison with the critical buckling load, the magnification factor is approximately unity indicating that the axial loading effect on the deflection is negligible. Thus, the value of the required section modulus is that necessary to resist bending under the normal hydrostatic load as if no compressive load were present. But when the loading approaches the critical value, the value of V approaches $^{\pi}/_{2}$, and the stiffener-plate combination collapses.

The selection of proper cross-sectional dimensions for the longitudinal must be made by iteration. Values of the primary and secondary stresses, as well as plate thicknesses are known each time a stiffener must be calculated. The strake width associated with each stiffener remains constant because the coordinates of stiffeners and plates have been fixed. Since the scantlings must have minimum values which satify A.B.S. requirements, the stiffener scantlings are initially chosen from Table 2 of the Rules. The section modulus of these stiffeners together with the associated plate is given in Ref. (10) by:

$$Z_{abs} = \frac{N \cdot L^2}{240} \tag{54}$$

where;

Z_{abs} = A.B.S. required section modulus

L = web spacing (length of beam)

N = $F_i \cdot h_i \cdot C$

c = constant depending on location of stiffener and the boundary conditions

i = particular stiffener considered

Chapter VIII discusses the fact that this formula defines the moduli of ABS stiffeners in combination with plates whose effective breadth is approximately 60 times the thickness. When the axial compressive loading is small compared to normal loading, Eq. (53) is shown to be closely related to Eq. (54).

The ABS value of section modulus is judged to be a lower limit because the section modulus prescribed is based upon the normal loading only. But this minimum value must resist the actual combined axial-lateral loading under the current stress schedule, without failure. Therefore the slenderness ratio, $\frac{L}{K}$, of the ABS plate-stiffener combination is substituted into Eq. (53) and the required section modulus to prevent buckling is determined. When the assumed combination is insufficient, the Z_T will be larger than the Z_{abs}. Therefore, a larger section modulus is tried in the next iteration. This new trial is taken as the mean of the assumed and required modulus in order to insure a convergence without oscillation. When the assumed section modulus yields a slenderness ratio that results in satisfaction of Timoshenko's relationship, the stiffener-plate combination is judged satisfactory.

As the section modulus of the trial section is increased, the stiffener increases in size and as a result, the neutral axis of the combination moves out toward the stiffener flange. This generally results in a smaller slenderness ratio and has less susceptibility to buckling failure.

Since every longitudinal must be redesigned for every change in stress schedule, and this cycling procedure must be carried out for each stiffener, vessels purely longitudinally framed require nearly twice the computer time as do purely transversely framed ships. As the number of longitudinals increase, they become a greater percentage of total cross sectional area. Since small increase or decrease in thicknesses also result in a corresponding change in stiffener scantlings, a relatively large change in cross sectional area may occur even though the change due to plate thickness variation itself is small. The primary stress would then vary more than might be expected from the small thickness variation. The weighting function used to change thicknessess should therefore be modified to account for the effect of stiffener area variation so that the rate of total section area change can not cause oscillations which would slow down convergence.

For the side longitudinals, a constant primary bending stress equal to the maximum stress on the side shell section was assumed. From Eq. (51) this assumption implies that the longitudinals are subjected to a constant secondary stress also. This is not altogether unreasonable and the ABS appears to determine its section modulus for longitudinals under such an assumption. The Rules require constant side plating thickness, also implying a constant primary stress or at least neglecting variations as a practical matter. The fact that the side shell is subjected to many lateral forces other than water pressure, for instance, warping and docking loads, lends rationality to this assumption. Another consideration is that shear loading increases with proximity to the ship's quarter length, so that additional strength should be provided near the neutral axis at such locations. Uniformity in the depth of the side longitudinals is desirable for cargo stowage since cargo battens can be attached to the stiffener flanges. The assumption of constant secondary bending stress over the side shell sections is obviously not an inherent requirement of the design synthesis. But the assumption is apparently in keeping with the philosophy of the ABS Rules for longitudinally framed cargo ships. For naval vessels, or for a more discriminating rational design, the actual stress can be used without upsetting the design.

Refinement of Plate Thickness

The thicknesses of the plating are now modified to meet the stress schedule set by the first three steps in the refinement. This is a significant phase of the design since the basic plate scantlings are now determined. As the design is aimed, at present, to satisfy A.B.S. Rules, the formulas for the plate thicknesses closely parallel A.B.S. criteria. Table 1 is a summary of all the thickness relationships based on normal loadings. These formulas are subject to revision when the design standards are changed.

A difficulty arises in the analysis of the boundary plates existing between two adjacent sections with different framing systems. This may occur on the side shell, where the plate seams have been determined without regard to the section boundaries. Therefore, plates overlap the section boundaries so that the two sections share a common plate. A thickness requirement must be stated for the common plate between two adjacent, but differently framed sections. This difficulty does not arise for the decks or bulkheads since the plate seams can not overlap boundaries for these sections.

For a ship which is to have any possible framing system, it would be impractical to fix the plate seams so that they do not overlap section boundaries. A method could be devised perhaps, but that would not be a practical solution of the problem since the only basis for disturbing the present arrangement would be the inability to analyse the existing seam geometry which was selected to approximate realistic practices.

FORMULAS FOR

PLATE THICKNESSES UNDER LATERAL LOADING

Plate Location	Transversely Framed ($t_i =$)	Ref.	Longitudinally Framed ($t_i =$)	Ref.
keel	$a\sqrt{\frac{K\ H}{2(S_y - S_1)}} + 0.17$	12	$1.5\ F\sqrt{\frac{21.9\ H}{S_3}}$	12 and 14
bottom and bilge	$a\sqrt{\frac{K\ H}{4.5(S_y - S_1)}} + 0.11$	12	$F\sqrt{\frac{21.9\ H}{S_3}}$	14
bulkhead and deck pltg.	$a\sqrt{\frac{K\ H}{4.5(S_y - S_1)}}$	9 and 12	$F\sqrt{\frac{21.9\ H}{S_3}}$	1 and 14

TABLE NO. 1

TABLE NO. 1(CONT.)

Plate Location	Transversely Framed (t_i=)	Ref.	Longitudinally Framed (t_i=)	Ref.
side shell	maximum of: 1) $a\sqrt{\frac{K\,H}{4.5(S_y-S_1)}}+0.11$ 2) $\frac{0.275\ LHB}{18500\ D}+0.11$ 3) $\frac{0.275\ BH}{21\ D}$ $(L<310)$ $\frac{0.275\ LBH}{(25.5L-1400)D}$ $(L\geq 310)$	9 9 12 12	$F\sqrt{\frac{21.9\ H}{S_3}}$	14
stringer strakes and center plt. on inner bot.	$a\sqrt{\frac{K\,H}{4.5(S_y-S_1)}}$	9	$F\sqrt{\frac{21.9\ H}{S_3}}$	14

TABLE NO. 1(CONT.)

Plate Location	Transversely Framed ($t_i=$)	Ref.	Longitudinally Framed ($t_i=$)	Ref.
sheer strake	maximum of: $\frac{(0.009\ L + 0.17)L}{121\ D}$ or side pltg.	12	maximum of: $\frac{(0.009\ L + 0.17)L}{121\ D}$ or side pltg.	12
top strake	average of; sheer strake and side pltg. thickness	12	average of; sheer strake and side pltg. thickness	12
inner bottom plates	$\frac{a\sqrt{K\ H}}{475.0} + 0.13$	9	$F\sqrt{\frac{21.9\ H}{S_3}}$	14
center vertical keel	main deck stringer plt. thickness		main deck stringer plt. thickness	

Rather than search for an exact solution, an expedient, but pragmatic approximation was sought. One approach might have been to test the strength requirements under the two framing systems and let the most severe requirement govern the design of the common plate. This solution breaks down when the most severe requirement applies to a plate which lies nearly completely in the section with the less stringent criteria, which would result in an excessive thickness requirement. The best approach seems to be to examine the plate seam and determine in which section most of the plate width exists, and let the framing system of that section determine the plate thickness.

When examining transversely and longitudinally framed panels, the boundary conditions are by no means exact. The only definite boundary conditions for ship's plating is that the degree of restraint lies between simple support and clamped conditions. The viewpoint adopted in this design synthesis in considering individual plate panels is to assume simple support along all edges for longitudinally framed panels, and clamped-loaded edges and free-unloaded edges for transversely framed sections. The fact that the boundary conditions are at best only assumptions, does not impose a limitation on the overall design synthesis, since it will only involve modifying the formulas in Table 1, should changes become necessary.

For transversely framed sections under lateral load, the midpoint of the panel's long side is critical and the allowed stress is:

$$(S_3)_i = (S_y)_i - (S_1)_i - (S_2)_i$$

where $(S_2)_i$ is approximately zero. But for longitudinally framed panels, the midpoint of the short side is critical and the S_2 stress is assumed 3000 psi. This could be verified during later cycles if desired.

$$(S_3)_i = (S_y)_i - (S_1)_i - 3000$$

The relationships are all standard structural formulas for plates under normal loads. The difficulties encountered in analysing plates with discontinuities of thickness are beyond the scope of basic design formulas. Therefore, when seams lie between supports, the discontinuities in thickness are ignored, and a panel of constant thickness equal to the thinnest plate is assumed in the analysis.

The specific plate requirements indicated by an asterisk in Table 1 have been taken directly from Ref. (8, 9, or 12) to reproduce ABS Rule requirements. Substitution for these standard formulas is easily made should ABS Rule requirements be ignored. The center vertical keel thickness is arbitrarily given the same thickness as the main deck stringer plate. This assumption is made only for convenience in the design and should be changed as soon as a reasonable relationship can be defined.

The mechanism used in changing the plate thicknesses is the central theme in this phase of the design. The formlulations listed in Table 1 are only limiting values on which the thickness modifications are converging. Since the new thicknesses are always designed from a stress schedule one step behind the current thicknesses, the final scantlings must be found by evolution rather than by direct substitution. No "a priori" knowledge exists about the final distribution of plating thickness and the corresponding stress schedule. Therefore, there is no justification for direct substitution of thicknesses. The best method for converging upon the ultimate solution is to change the existing plate thicknesses, determine the new stress schedule, and then change the thicknesses again, until the new stress schedule matches the previous one.

The old and new thicknesses may be related by the formula:

$$(T_i)_N = \frac{(T_i)_R + w \cdot (T_i)_o}{w + 1} \tag{55}$$

where:

$(T_i)_N$ = new plating thickness.

$(T_i)_o$ = old plating thickness from previous refinement.

$(T_i)_R$ = thickness required under normal loading to meet stress schedule.

w = weighted averaging factor.

As seen in Eq. (55), the new thicknesses are simply a weighted average of the old thicknesses and the thicknesses required by the current stress schedule.

During this refinement procedure based upon normal loading in Cycle 1, all plates are changed according to Eq. (55), but in subsequent design cycles this change must be directed away from certain plates which have been changed to meet other criteria. More specifically, these are the plates that buckle and the plates whose thicknesses have been increased to satisfy the deficiency in primary bending strength. Should these plates be continuously changed according to normal load, the increase of thicknesses to these plates would be destroyed. Therefore, the plate thicknesses which have been increased to satisfy either buckling or bending strength in Cycle 1, should not be changed by the refinement based on normal loading in Cycle 2, and in subsequent design cycles. Thus, a record of all plates which have been changed to satisfy buckling and bending strength requirements must be kept. This can present a bookkeeping problem since the set of initial thicknesses selected for Cycle 2 and subsequent cycles are those from either Cycle A or Cycle B of the previous design cycle. This problem can be solved by assuming that the location of plates which buckle are in regions of highest stress. Since the regions of highest stress level and the location of plates whose thicknesses are best increaaed to satisfy limiting stress requirements coincide, the problem is reduced to specifying these regions during each design cycle.

When the top fibers are found deficient in primary bending strength, all plates above the topstrake are designated as being regions of high stress. Similarly, the bottom plating up to the top of the bilge is the region of high stress when bottom fibers are found deficient in bending strength. The assumption that plates which buckle be in regions of highest stress may not be entirely true for all ship designs. A more concise method should be developed which ensures that the correct plates are being refined under normal loading, and so that the increase of thicknesses in a previous cycle is not destroyed.

The weighting function used in Eq. (53) is developed to make the most rapid change in plate thicknesses be proportional to the distance of a plate from the location of strength deficiency. Examination of Eq. (55) will reveal that for values of w greater than one, the new thickness will be closer to the old thickness than to the new required thickness, so the rate of change of thicknesses may be slowed by increasing w. The various values of w are listed below:

When the top fibers are deficient in primary bending strength:

$$w = 6 - \frac{3Y_i}{D} \tag{56}$$

When the bottom fibers are deficient in primary bending strength:

$$w = 3 + \frac{3Y_i}{D} \tag{57}$$

When both top and bottom fibers are deficient:

$$w = 3 + \frac{3(S_1)_i}{(S_1)_{bottom}} \tag{58}$$

When both top and bottom fibers are satisfactory, the weighting function is given a constant value of 3.5.

The purpose of defining various values for w is to minimize the number of refinement cycles. Since a definite limit has been placed on the number of refinement cycles in order to conserve computation time, the best refinement is made with a continually varying weighting function.

The implications of each step in the refinement process are carried throughout the entire synthesis. Errors can be very costly at this step in the design. However, none of the assumptions made thus far are of the type which are critical to the design logic. Each assumption has been made after careful consideration of the alternatives. When better assumptions are developed, they may be implemented without upsetting the basic design philosophy.

CHAPTER V

THE MAIN CYCLE

General Description

Upon completion of the refinement subcycle, the hull structure is capable of resisting local loading of the plate panels under the imposed stress schedule. The synthesis now considers the hull girder as a simple beam in bending. The criterion first examined is the limiting hull girder stress restriction, then resistance to buckling is examined. The design philosophy is to satisfy both restrictions independently. Therefore at the completion of the refinement subcycle, the design cycle branches into two iterations, called Cycle A and Cycle B.

The scantlings determined from the refinement subcycle are checked for satisfaction of the limiting primary stress restriction before entering Cycle A. If deficient, the scantlings must be modified by increasing the thicknesses of plates located in critical stress regions.

For purposes of defining these regions, the hull cross section is divided into top and bottom sections. The bottom is defined as all plating below the current ship neutral axis. The top section is all plating lying above the neutral axis. Cycle A attempts to satisfy any deficiency in bending strength by increasing the thicknesses of plates that are most efficient in reducing the primary stress. These plates will be the ones located at the fibers most distant from the neutral axis. Cycle B is similar in operation to Cycle A except that it attempts to satisfy the limiting primary stress criterion by increasing the thickness of plates which are found to buckle. Both cycles act on the same set of scantlings, but yield different results because the plate thicknesses to be varied are selected under different criteria.

Cycle A begins with a definition of the plates whose scantlings are to be changed. The amount that each plate thickness is incremented must also be set. Since those plates at the extreme fibers are most efficient in reducing the primary stress, the keel plate is selected to absorb one-third of any of the thickness additions on the bottom. The other two thirds will be evenly distributed over the bottom shell up to the top of the bilge turn. Any additions to the top plating will be distributed such that one-twelfth of any thickness additions is added to the top side shell and sheer strakes, one-sixth to the stringer strake, and the remainder distributed over main deck plating. These ratios are subject to modification, but were set to avoid any abrupt discontinuities in plate thicknesses.

Linear Extrapolation

The method of satisfying limiting primary stress is a direct application of the linear extrapolation found in Ref. (14). A linear relationship is assumed between area addition and decrease in stress. Although this relationship is in reality nonlinear, for small changes the linearity assumption holds. Figure 7 is a general representation

TYPICAL STRESS-AREA RELATIONSHIP

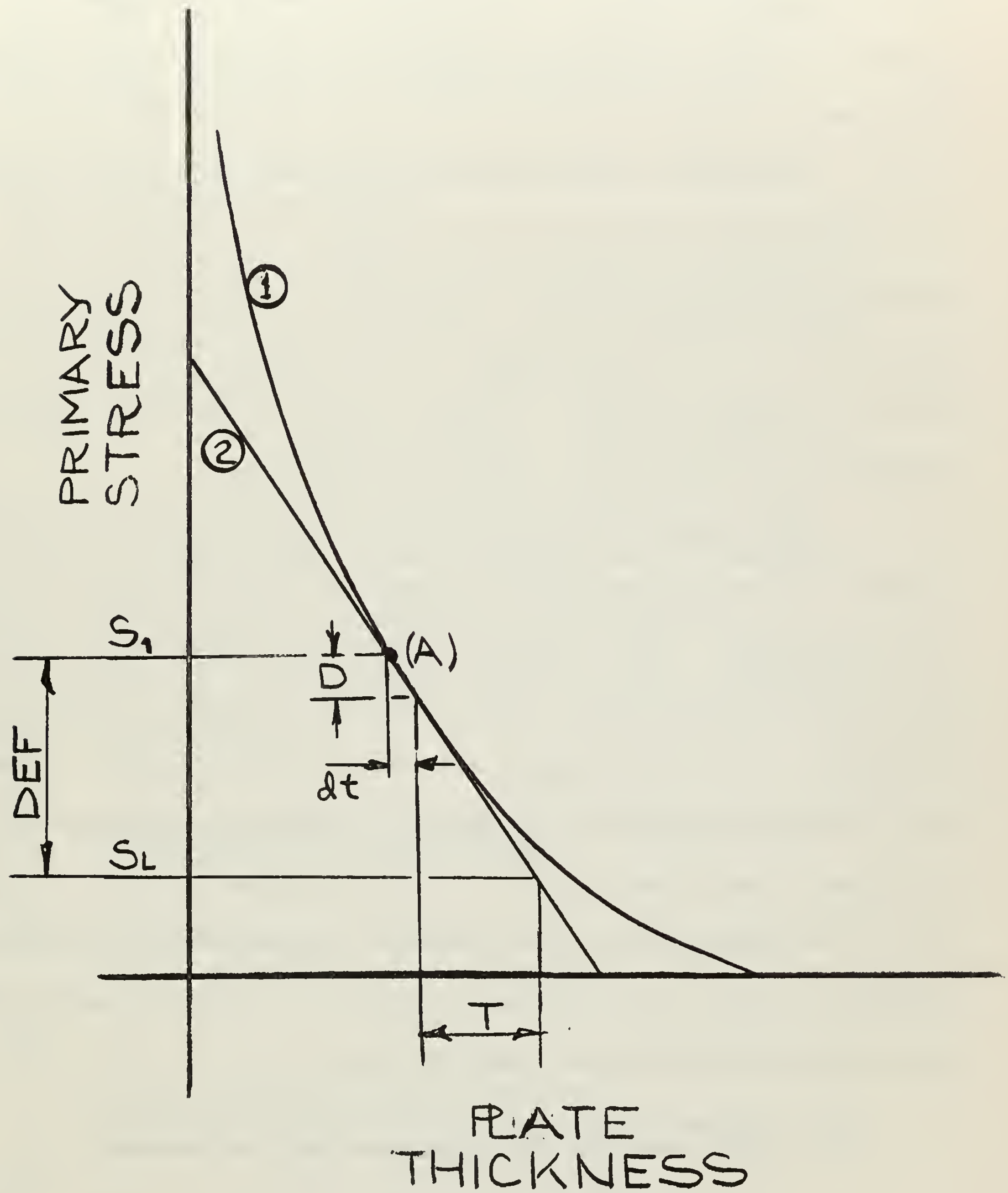


FIG. 7

of this assumption. The actual stress-area, (stress - thickness), relationship is found as in Curve 1, while the assumed relationship is represented by Curve 2. The linear extrapolation begins at a point A. A small incremental increase in area will cause a correspondingly small decrease in stress. This will determine the slope of the line 2. The actual required decrease in stress, $(S_1 - S_L)$, can then be extrapolated using the slope of the line. The resulting area increase will not satisfy the limit stress requirements due to the nonlinearity of the relationship. But each succeeding cycle will require a smaller decrease in stress, therefore the resulting area increases will more nearly approach satisfaction.

The linear program begins with a definition of the stress schedule due to increments of thickness at either the top or bottom of the hull girder. Small thickness additions are made to the plates in the top section which have been designated to absorb the thickness additions, and the resulting stress schedule is calculated. Similarly, the bottom plates selected to absorb the thickness additions are increased a small amount and the resulting stress schedule is found. Also, the stress deficiency at both the top and bottom fibers are determined using the thicknesses calculated in the refinement subcycle. The values defined by this operation are:

D_{11} The small change in primary stress, S_1, at the top fiber when the top thicknesses are incremented.

D_{12} The small change in primary stress, S_1, at the top fiber when the bottom thicknesses are incremented.

D_{21} The small change in primary stress, S_1, at the bottom fiber when the bottom thicknesses are incremented.

D_{22} The small change in primary stress, S_1, at the bottom fiber when the bottom thicknesses are incremented.

∂t_1 The small increase in thicknesses of the top plates.

∂t_2 The small increase in thicknesses of the bottom plates.

DEF_1 The stress deficiency in the top fiber at the end of the refinement subcycle.

DEF_2 The stress deficiency in the bottom fiber at the end of the refinement subcycle.

The above values are sufficient to determine the slopes of the line relating the areas to the stresses. The thickness increase is used as a direct representation of the area increase.

Enough information exists to define a linear program which will add enough area at the correct locations to satisfy the limit stress. The linear program used in this synthesis is an elementary two-dimensional application of the general problem described in Reference (4). Figure 8 is a graphical representation of the problem where the symbols are defined:

$X_{11} = \frac{D_{11}}{\partial t_1}$ rate of decrease in stress at the top fiber due to an increase of top thicknesses.

$X_{12} = \frac{D_{12}}{\partial t_2}$ rate of decrease in stress at the top fiber due to an increase of bottom thicknesses.

$X_{21} = \frac{D_{21}}{\partial t_1}$ rate of decrease in stress at the bottom fiber due to an increase of top thicknesses.

$X_{22} = \frac{D_{22}}{\partial t_2}$ rate of decrease in stress at the bottom fiber due to an increase of bottom thicknesses.

LINEAR PROGRAM

MINIMIZE: $I = A_1T_1 + A_2T_2$

SUBJECT TO:

(1) $X_{11}T_1 + X_{12}T_2 \geq DEF_1$

(2) $X_{21}T_1 + X_{22}T_2 \geq DEF_2$

(3) $T_1 \geq 0$

(4) $T_2 \geq 0$

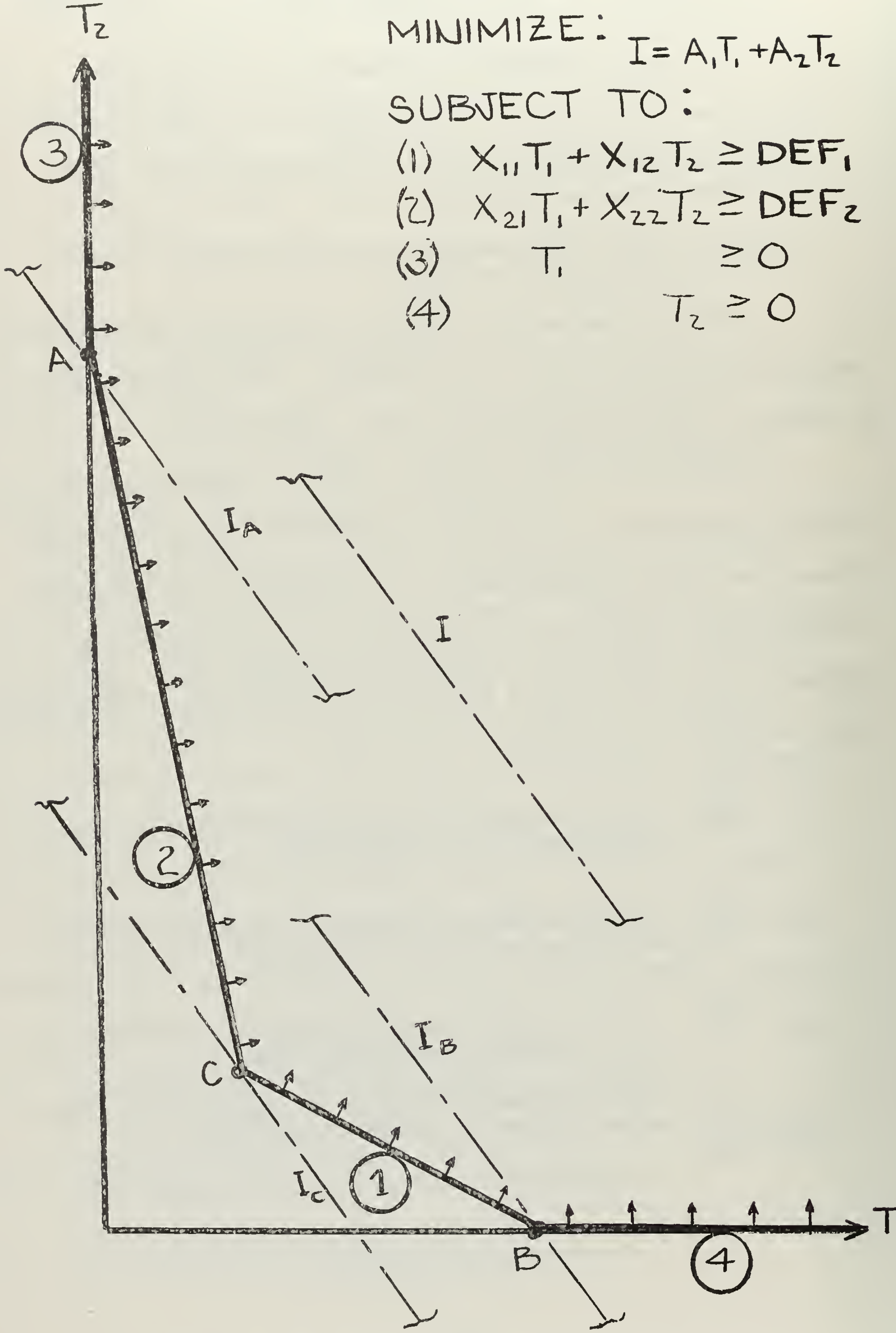


FIG.8

A_1 rate of area increase at the top due to unit thickness increase.

A_2 rate of area increase at the bottom due to unit thickness increase.

T_1 all plate thicknesses added to top.

T_2 all plate thicknesses added to bottom.

I the total amount of area added to the hull cross section by the linear program.

The linear programming problem is to minimize the total area added, subject to the constraints imposed by the limit stress. Intuitively however, certain facts lead to a simple graphical solution.

Since area is to be only added to the cross section, the slope of I is negative as shown in Fig. 8. The only possibilities for a solution which minimizes I and also satisfies the constraints are the points A, B, or C, which are extreme points of the convex region. Without calculating values of I, it is known that if only the top stress is deficient, then the slope of I will be so steep that point A will be the solution and only thickness additions to the top plates yield the minimum area to be added. Similarly, if only the bottom stress is excessive, point B will be the solution and only thickness additions to the bottom plates yield the minimum area. But if both stresses are deficient, then area must be added to both bottom and top plating. This is reflected in Fig. 8 by the line I_c at the point C, which yields the minimum value of I.

The values of T_1 and/or T_2 corresponding to the solution point are distributed over the previously defined top and/or bottom plating, and the linear program is complete. As mentioned in Chapter IV, everytime the plate thicknesses and stress schedule are varied the stiffener scantlings must be modified. This operation is, therefore, carried on through the main cycle to keep the stiffener values compatible with the current stress schedule.

The stress schedule resulting from the linear program will satisfy the limit stress restriction only if the original deficiency is small, since linearity only holds over a very small portion of the stress-area relationship. If the deficiency was large, subsequent cycling will result in satisfaction of the limit stress requirement. Should the solution to the linear program result in satisfaction of the limit stress, plates could still buckle under the existing stress schedule. As a final check, the plates susceptible to buckling are increased by the method described in Chapter VI.

Cycle B, as mentioned earlier, is very similar in operation to Cycle A. The plate thicknesses as determined by the refinement subcycle are examined for buckling failure. These plates are then divided into appropriate top and bottom sections. The linear program is again performed as in Cycle A and the results are checked for buckling failure if the limit stress is satisfied.

G. Recycling

Now that one design cycle is completed, several alternatives present themselves. An interruption is made in the cycling process in order to sort out the alternatives and tabulate the results.

One possibility is that the design is complete. This would mean that the scantlings derived in Cycle A and/or Cycle B satisfy all required criteria. When both cycles satisfy the governing restrictions, the least weight solution scantlings corresponding to either cycle would be the final solution. Should only one of the cycles fulfill all restrictions, it might be chosen as the final solution. The inadequate results of the other cycle could be reiterated, but then results from new Cycles A and B occur, so that selection must now be made from three sets of solution scantlings. This sequence of eventualities is unlikely because of the inherent operation in the linear program. Although Cycles A and B operate on different plates, the resulting stress decrements are approximately the same since the operations of the linear program in both cycles attempt to satisfy the same deficiency in limit stress. The area additions may differ because the plates that are operated upon by the linear program in the two cycles may be in different locations on the hull girder. Thus the results of Cycles A and B are generally satisfactory simultaneously.

When the design is terminated with Cycle A or Cycle B, the increase of plating thickness by the linear program or by the buckling strength requirement decreases S_1 and relaxes the S_3 restriction. The present synthesis fails to refine the plate thicknesses due to the relaxation of the S_3 stress. However, recycling does produce this refinement, and implementation of the refinement process at the ends of both Cycle A and B is easily done.

When the results of both Cycles A and B are deficient in bending strength, further iteration is necessary and a choice must be made between the results of A or B for starting the new design cycle. An "a priori" decision must be made based upon existing data as to which selection will eventually yield the least weight solution. Pertinent data to consider are the normalized weight and the degree of inadequacy in bending and buckling strength for the two cycles.

Unfortunately, any indications as to the final least weight solution can be deceiving. The current least weight solution may yield a greater weight at the end of the next design cycle than would the selection of the current greatest weight solution. This could occur if the greater weight solution were closer to satisfying the stress criteria. Investigation may determine the relationship between weight and the degree of stress satisfaction. However, any meaningful relationship to predict the consequences of a given selection must cover all possibilities and the number of possibilities being 2^n where n is the number of design cycles. This uncertain aspect of the design should be eliminated. A slight change in the design philosophy could remove any need for human intervention, but extensive revision of the computer program would be necessary. The explanation which follows is a means of eliminating human intervention without changing the general theory of the design process.

Alternate Cycling Procedure

Rather than making two attempts at satisfying limit stress using plates in the linear program that are selected under different criteria, a single consecutive examination might be made. In the present design process, the plate scantlings determined by the refinement subcycle are examined for buckling strength in Cycle B. Those scantlings which are deficient in buckling strength are increased to satisfy the bending strength requirements by the linear program in Cycle B. The change under discussion would be to examine the scantlings resulting from Cycle A for buckling, and to increase those plates that buckle by a linear program based on the deficiency in buckling stress. The difficulty of this change is in the linear program. Since the deficiency in buckling stress will be the governing criteria for determining the rate of increase in plate thicknesses, a new linear program must be developed. Investigation would be necessary to determine the degree of linearity between plate thickness increases and reductions in buckling stress deficiency. An attempt to use the present linear program again to satisfy buckling strength fails because the rate of increasing plate thicknesses depends on the degree of primary stress deficiency. Since the present linear program is based on limit stress deficiency, after Cycle A the deficiency will have been greatly reduced or may even be zero. Thus, any attempt to satisfy buckling strength based on this reduced deficiency would fall short of its goal.

Should this alteration prove feasible, there would be no need for human intervention. Results at the end of each cycle would be displayed as in the present design, but cycling would be automatic because only one set of scantlings would be developed in an attempt to satisfy both buckling and bending strength requirements simultaneously.

The present synthesis does not yield erroneous results because of the necessary interruption. The complete design requires, at most, three cycles and the comparisons between Cycle A and B yield similar scantlings.

CHAPTER VI

Buckling Investigation

Plating thicknesses thus far have been determined according to local hydrostatic loads and primary bending strength criteria. At some point in the design, local stability under compressive loading should be tested. This type of failure is due to buckling of the panels between supports and does not include buckling of the plate-stiffener combination which has already been examined for first cycle conditions.

The design philosophy is to best satisfy all governing criteria without emphasizing one at the expense of another. Examination for plate buckling should be integrated within the design so that an attempt can be made at satisfying this restriction in an optimum manner. Presently, plates are checked at two stages of the design; at the beginning of Cycle B in order that appropriate plate thicknesses may be increased; and then at the end of both Cycles A and B in case all other criteria are met with plates still liable to buckle.

Two formulations are used to predict instability failure. For sections which are longitudinally framed, Bryan's formula is used.

$$S_{cr} = \frac{K\pi^2 \cdot E \cdot T_i^2}{12(1-\mu^2)F_i^2} \qquad (59)$$

where,

S_{cr} = Critical buckling stress

F_i = Frame spacing associated with T_i

μ = Poisson's ratio

K = Constant depending upon aspect ratio and boundary conditions.

Within longitudinally framed systems, plate seams lie between longitudinals sometimes resulting in panels with thickness discontinuities. The panel thickness used in Bryan's formula will be that of the thinnest plate, resulting in the most conservative critical stress. Transversely framed sections are analyzed by Montgomerie's formula, based upon the boundary conditions assumed for transversely framed panels.

$$S_{cr} = \frac{40{,}300}{1 + \frac{1}{950}\left(\frac{a}{T_i}\right)^{1.75}} \qquad (60)$$

where,

a = transverse frame spacing.

Again, differing thicknesses occur within each section. The problem in this case is different from that of longitudinally framed sections. There, only two different thicknesses are possible; and so a simple assumption is possible. Here, choice of the thinnest plate is erroneous because the next size plate thickness might buckle also. In the present design, all strakes are examined with the assumption that the thickness of the plate being examined extends over the whole section. In this way, a conservative test is made since the contribution of the thicker plates is ignored. The thickness of all susceptible plates will be increased; so if more than one plate in a section buckles, the assumption that each thickness extends over the section is plausible, even for plates not necessarily the thinnest. An argument may arise that this method is overly conservative, since more thickness than necessary will be added to the less susceptible plates. However, if only the thickness of the thinnest plate is increased, all the necessary thickness to satisfy primary bending will be added to just one plate, resulting in an unrealistic thickness distribution. The present arrangement seems to be the most pragmatic choice under all eventualities.

At the point in the design development before Cycle B, plates are only checked for buckling failure. The satisfaction of buckling criteria is not attempteddirectly, but instead the linear extrapolation will increase the plate thicknesses under primary stress criteria. Should the limiting stress be satisfied, the thicknesses of these plates must be directly varied, but in an optimum manner.

By rearranging Equations (59) and (60), the necessary plate thickness under the current stress schedule may be determined.

For transversely framed sections, Eq. (60) becomes:

$$T_{req} = \frac{a}{\left[950\left(\frac{40{,}300}{S_1}\right) - 1\right]^{1/1.75}} \tag{61}$$

and for longitudinally framed sections, Eq. (59) becomes:

$$T_{req} = F_i \sqrt{\frac{12\,(1-\mu^2)S_1}{K\pi^2\,E}} \tag{62}$$

Since increasing plate thicknesses will relax the stress schedule, directly replacing deficient plates with the required values will result in over-compensation. Therefore, the deficient and required thicknesses are averaged and the new stress schedule is again checked. When the difference between the required and actual thickness becomes negligible, the iteration is terminated and the deficiency is alleviated. This iteration is the final step of the design and is only necessary when all other criteria have been satisfied.

An example may help demonstrate the optimality of the present scheme of thickness variation. When the limit stress is unsatisfied, the feasibility of using two separate cycles is apparent, but should limit stress be satisfied by the distribution of thicknesses based upon normal loading, then Cycles A and B are unnecessary. Perhaps a direct choice might have been made in the original refinement between the most stringent requirement, that of normal loading, or that of buckling instability. This is the method used in References (8) and (12). The same effect is achieved by the present synthesis. First, normal loading is satisfied, and then buckling is prevented by incrementing deficient plate thicknesses. The relaxation of the stress schedule allows thinner plates elsewhere and, therefore, this method best satisfies all criteria.

CHAPTER VII

Discussion of Initial Thicknesses

In order to satisfy the promise that the final scantling results will be optimal, the selection of arbitrary initial scantlings must be shown to converge upon a unique solution. The following discussion, together with some sample trials, demonstrate that any reasonable plate thicknesses may be chosen initially. Then these thicknesses can be refined to a unique and final set of scantlings.

Requiring that the initial selection be reasonable, implies only that good engineering judgment be used. For example, selection of extremely thick plates will require many cycles in the refinement subcycle to reach the final solution. When very thin plates are selected, a more serious consequence arises. The resulting cross sectional area may become so small that the primary bending stress exceeds $\frac{S_y}{1.25}$. As a result, S_2 from Eq. (49) becomes negative by Eq. (51) and the design process breaks down. A safeguard has been built into the synthesis which increases all the thicknesses before the first trial when the initial plate scantlings are too thin.

The problem of inadequate cross sectional section modulus arises with large shallow ships. Under lateral plate loading, the thickness requirement is not severe because of the small water head due to shallow draft. However, the resulting ship section modulus, together with a large bending moment may define large primary stresses. Therefore, even though adequate plate thicknesses are initially selected, the refinement subcycle may drive these thicknesses down to values which cause a breakdown in the design. The safeguard mentioned above halts the refinement when indication of this trouble arises. This explanation will be developed further when the refinement process has been fully demonstrated.

The demand that the arbitrary initial thickness selection be reasonable should not be viewed as a restriction, since the only penalty is excessive computation time, not an incorrect solution.

A singular solution is found by subjecting the scantlings to two independent constraints. The magnitude and distribution of the hull cross sectional area must be unique. The plate thicknesses govern the design since the stiffeners are calculated after the plate scantlings. During the refinement of the plate thicknesses, the stiffener scantlings are also changed. But because the stiffeners are a small percentage of the total cross sectional area, and since the refinement process is carried out at a slow rate, any fluctuations of stiffener scantlings will not affect the refinement of the plate thicknesses to any degree.

The distribution of the initial plate thicknesses is governed entirely by local loading. The thicknesses used are either those required by local hydrostatic loads (with due allowance for other loadings) or in a few cases, by the ABS Rules. The final orientation will be according to one of these local demands.

Initially, the thicknesses may be larger or smaller than the final refined thicknesses. In either case, the final distribution will be unique with the greatest thicknesses on the bottom, and decreasing up the side of the hull. Should the initial thicknesses be excessive, the resulting primary stress will be low because the cross section is large. Therefore, the tertiary stress allowance is more liberal for each plate, permitting a decrease of the plate thicknesses. Smaller plate thicknesses decrease the hull cross sectional area and increase the primary stress. This, in turn, decreases the allowable tertiary stress which may or may not permit the plate thicknesses to be decreased further. Convergence is reached when the tertiary stress requirement no longer allows the thicknesses to be decreased. In a similar fashion, when the initial cross sectional area is deficient, the tertiary stress requirement is too severe and plate thicknesses must be increased. As a result, the primary stress is lowered, the tertiary stress allowance is relaxed, and the plate thicknesses may be further increased. When thicknesses have been increased sufficiently so that the tertiary stress requirement is satisfied, convergence is reached. The variation of plate thicknesses does not affect the area distribution because hydrostatic loadings are solely a function of the geometry and are independent of the stress limitations.

Therefore, regardless of whether the hull cross section is initially too large or too small, the direction of refinement is to converge upon a unique set of plate thickensses. The magnitudes of the unique set determine a primary stress by Eq. (50). When substituted into Eq. (1), the resulting tertiary stress is equal to the allowed tertiary stress and the unique solution under normal load requirements is reached.

Table 2 demonstrates the convergence of two widely different initial thickness selections. The selection of the weighting function determines the rate of convergence. The weighting function can be viewed as a means of slowing down the convergence so that oscillation does not occur. Should plate thicknesses that are initially too large be immediately decreased to the value required by the current stress schedule, the resulting hull cross section will cause a large bending stress. The problem of a negative tertiary stress arises if this new cross section is so small that the primary stress becomes greater than $\frac{S_y}{1.25}$. The use of a weighting function avoids this problem of oscillation by modifying the current thicknesses only a small amount in favor of the new ones.

Table 2 is a typical iteration for achieving plate scantlings required under local lateral loading. The hull girder investigated is a 550 foot "Mariner" type vessel with three decks, an inner bottom, and longitudinal framing of the top deck and the double bottom. The Table only shows results for plates on the shell from the keel up to the main deck. The "Primary Stress" is that bending stress resulting from the cross section defined by the thicknesses under the column titled, "Old Plate". The plate thicknesses required by the current tertiary stress are under the "Req'd Plate" column. The "Weighting Function" is defined by Eq. (48) which averages the old and required plates to a "Refined Plate" which becomes the "Old Plate" of the next subcycle. For the first iteration, the initial thicknesses are under the column titled, "Old Plate", and cause the primary stresses shown in Subcycle No. 1.

For Trial A, an initial distribution was selected which yields a small cross section, with most of the deficient plate thicknesses occurring at the top of the shell. The task of the refinement is to increase the thicknesses of the top plates while decreasing those of the bottom plates. The thicknesses required by the top plates (0.404") are taken from the ABS Rules so that the value of the weighting function is not demonstrated in this location. Since stress is related to the square of the thicknesses, the stress variation is very sensitive to thickness changes in regions of high stress, while less sensitive in lower stress regions. Therefore, in the general case, the decision was made to retard the rate of convergence in these high stress areas.

As the refinement is followed through Trial A, the orientation of the thicknesses is rotated to conform to the required plate thickness distribution under normal loading with each plate thickness varied toward that required by the lateral loads. A study of the stress schedule will show a decrease in top stress and an

INITIAL THICKNESS SELECTION

NO.	PLATE THICKNESS
1	.800
2	.800
3	.800
4	.800
5	.800
6	.799
7	.778
8	.736
9	.685
10	.633
11	.581
12	.530
13	.478
14	.426
15	.374
16	.323
17	.267
18	.212

TRIAL A
TABLE NO. 2

HISTORY OF THICKNESS REFINEMENT

CYCLE NO. 1 SUB-CYCLE NO. 1

NO.	REFINED PLATE	WEIGHTING FUNCTION	OLD PLATE	REQ'D PLATE	PRIMARY STRESS
1	.746	3.000	.800	.585	5990.96
2	.700	3.000	.800	.398	5990.96
3	.704	3.000	.800	.417	5990.96
4	.709	3.000	.800	.435	5990.96
5	.713	3.000	.800	.453	5990.96
6	.716	3.005	.799	.469	5946.81
7	.703	3.111	.778	.469	5012.33
8	.673	3.326	.736	.463	3119.94
9	.684	3.587	.685	.682	817.75
10	.634	3.851	.633	.639	1509.47
11	.584	4.115	.581	.592	3836.70
12	.532	4.379	.530	.540	6163.93
13	.479	4.643	.478	.481	8491.15
14	.424	4.907	.426	.411	10818.38
15	.379	5.171	.374	.404	13145.61
16	.335	5.435	.323	.404	15472.83
17	.288	5.718	.267	.404	17960.52
18	.240	6.000	.212	.404	20448.20

TRIAL A

TABLE NO. 2 (CONT.)

HISTORY OF THICKNESS REFINEMENT

CYCLE NO. 1 SUB-CYCLE NO. 2

NO.	REFINED PLATE	WEIGHTING FUNCTION	OLD PLATE	REQ'D PLATE	PRIMARY STRESS
1	.707	3.000	.746	.588	6260.66
2	.625	3.000	.700	.401	6260.66
3	.633	3.000	.704	.420	6260.66
4	.641	3.000	.709	.438	6260.66
5	.649	3.000	.713	.455	6260.66
6	.655	3.005	.716	.471	6219.53
7	.647	3.111	.703	.471	5349.01
8	.625	3.326	.673	.466	3586.16
9	.679	3.587	.684	.661	1441.55
10	.631	3.851	.634	.620	726.38
11	.582	4.115	.584	.575	2894.31
12	.530	4.379	.532	.525	5062.24
13	.477	4.643	.479	.468	7230.17
14	.420	4.907	.424	.404	9398.10
15	.383	5.171	.379	.404	11566.03
16	.346	5.435	.335	.404	13733.96
17	.305	5.718	.288	.404	16051.36
18	.263	6.000	.240	.404	18368.77

TRIAL A

TABLE NO. 2 (CONT.)

HISTORY OF THICKNESS REFINEMENT

CYCLE NO. 1 SUB-CYCLE NO. 3

NO.	REFINED PLATE	WEIGHTING FUNCTION	OLD PLATE	REQ'D PLATE	PRIMARY STRESS
1	.678	3.000	.707	.591	6455.68
2	.569	3.000	.625	.402	6455.68
3	.580	3.000	.633	.422	6455.68
4	.591	3.000	.641	.440	6455.68
5	.601	3.000	.649	.457	6455.68
6	.610	3.005	.655	.473	6412.81
7	.604	3.111	.647	.473	5505.30
8	.589	3.326	.625	.467	3667.53
9	.677	3.587	.679	.668	1431.80
10	.630	3.851	.631	.626	828.25
11	.582	4.115	.582	.581	3088.30
12	.530	4.379	.530	.530	5348.35
13	.476	4.643	.477	.472	7608.40
14	.418	4.907	.420	.404	9868.45
15	.387	5.171	.383	.404	12128.51
16	.355	5.435	.346	.404	14388.56
17	.320	5.718	.305	.404	16804.43
18	.283	6.000	.263	.404	19220.31

TRIAL A
TABLE NO. 2 (CONT.)

HISTORY OF THICKNESS REFINEMENT

CYCLE NO. 1 SUB-CYCLE NO. 4

NO.	REFINED PLATE	WEIGHTING FUNCTION	OLD PLATE	REQ'D PLATE	PRIMARY STRESS
1	.656	3.000	.678	.591	6489.78
2	.528	3.000	.569	.403	6489.78
3	.541	3.000	.580	.422	6489.78
4	.553	3.000	.591	.440	6489.78
5	.565	3.000	.601	.458	6489.78
6	.576	3.005	.610	.474	6447.99
7	.573	3.111	.604	.474	5563.59
8	.561	3.326	.589	.468	3772.63
9	.674	3.587	.677	.662	1593.82
10	.628	3.851	.630	.620	608.69
11	.580	4.115	.582	.575	2811.19
12	.529	4.379	.530	.525	5013.69
13	.475	4.643	.476	.468	7216.20
14	.415	4.907	.418	.404	9418.70
15	.390	5.171	.387	.404	11621.20
16	.363	5.435	.355	.404	13823.71
17	.332	5.718	.320	.404	16178.07
18	.301	6.000	.283	.404	18532.43

TRIAL A

TABLE NO. 2 (CONT.)

HISTORY OF THICKNESS REFINEMENT

CYCLE NO. 1 SUB-CYCLE NO. 5

NO.	REFINED PLATE	WEIGHTING FUNCTION	OLD PLATE	REQ'D PLATE	PRIMARY STRESS
1	.640	3.000	.656	.592	6575.14
2	.497	3.000	.528	.403	6575.14
3	.511	3.000	.541	.423	6575.14
4	.525	3.000	.553	.441	6575.14
5	.539	3.000	.565	.459	6575.14
6	.551	3.005	.576	.475	6533.04
7	.549	3.111	.573	.475	5641.92
8	.540	3.326	.561	.469	3837.34
9	.671	3.587	.674	.662	1641.98
10	.627	3.851	.628	.621	577.25
11	.579	4.115	.580	.576	2796.48
12	.529	4.379	.529	.525	5015.72
13	.473	4.643	.475	.468	7234.95
14	.414	4.907	.415	.404	9454.19
15	.392	5.171	.390	.404	11673.42
16	.369	5.435	.363	.404	13892.66
17	.343	5.718	.332	.404	16264.90
18	.315	6.000	.301	.404	18637.15

TRIAL A

TABLE NO. 2 (CONT.)

HISTORY OF THICKNESS REFINEMENT

CYCLE NO. 1 SUB-CYCLE NO. 6

NO.	REFINED PLATE	WEIGHTING FUNCTION	OLD PLATE	REQ'D PLATE	PRIMARY STRESS
1	.628	3.000	.640	.593	6607.14
2	.473	3.000	.497	.404	6607.14
3	.489	3.000	.511	.423	6607.14
4	.504	3.000	.525	.441	6607.14
5	.519	3.000	.539	.459	6607.14
6	.532	3.005	.551	.475	6565.37
7	.531	3.111	.549	.475	5681.24
8	.523	3.326	.540	.469	3890.83
9	.669	3.587	.671	.660	1712.70
10	.625	3.851	.627	.619	489.11
11	.578	4.115	.579	.574	2690.93
12	.528	4.379	.529	.524	4892.75
13	.472	4.643	.473	.467	7094.56
14	.412	4.907	.414	.404	9296.38
15	.394	5.171	.392	.404	11498.20
16	.375	5.435	.369	.404	13700.02
17	.352	5.718	.343	.404	16053.65
18	.328	6.000	.315	.404	18407.27

TRIAL A
TABLE NO. 2 (CONT.)

HISTORY OF THICKNESS REFINEMENT

CYCLE NO. 1 SUB-CYCLE NO. 7

NO.	REFINED PLATE	WEIGHTING FUNCTION	OLD PLATE	REQ'D PLATE	PRIMARY STRESS
1	.619	3.000	.628	.593	6641.88
2	.456	3.000	.473	.404	6641.88
3	.473	3.000	.489	.423	6641.88
4	.489	3.000	.504	.442	6641.88
5	.504	3.000	.519	.459	6641.88
6	.518	3.005	.532	.475	6600.14
7	.517	3.111	.531	.475	5716.56
8	.511	3.326	.523	.470	3927.27
9	.667	3.587	.669	.659	1750.50
10	.624	3.851	.625	.618	449.94
11	.577	4.115	.578	.573	2650 /38
12	.527	4.379	.528	.523	4850.82
13	.471	4.643	.472	.467	7051.26
14	.411	4.907	.412	.404	9251.70
15	.396	5.171	.394	.404	11452.14
16	.379	5.435	.375	.404	13652.58
17	.360	5.718	.352	.404	16004.73
18	.339	6.000	.328	.404	18356.89

TRIAL A

TABLE NO. 2 (CONT.)

HISTORY OF THICKNESS REFINEMENT

CYCLE NO. 1 SUB-CYCLE NO. 8

NO.	REFINED PLATE	WEIGHTING FUNCTION	OLD PLATE	REQ'D PLATE	PRIMARY STRESS
1	.613	3.000	.619	.594	6678.34
2	.443	3.000	.456	.404	6678.34
3	.460	3.000	.473	.424	6678.34
4	.477	3.000	.489	.442	6678.34
5	.493	3.000	.504	.460	6678.34
6	.507	3.005	.518	.476	6636.70
7	.507	3.111	.517	.476	5755.25
8	.501	3.326	.511	.470	3970.26
9	.665	3.587	.667	.658	1798.73
10	.622	3.851	.624	.617	396.42
11	.576	4.115	.577	.572	2591.57
12	.526	4.379	.527	.523	4786.72
13	.470	4.643	.471	.466	6981.87
14	.410	4.907	.411	.404	9177.02
15	.397	5.171	.396	.404	11372.17
16	.383	5.435	.379	.404	13567.32
17	.367	5.718	.360	.404	15913.82
18	.348	6.000	.339	.404	18260.33

TRIAL A

TABLE NO. 2 (CONT.)

HISTORY OF THICKNESS REFINEMENT

CYCLE NO. 1 SUB-CYCLE NO. 9

NO.	REFINED PLATE	WEIGHTING FUNCTION	OLD PLATE	REQ'D PLATE	PRIMARY STRESS
1	.608	3.000	.613	.594	6714.11
2	.434	3.000	.443	.405	6714.11
3	.451	3.000	.460	.424	6714.11
4	.468	3.000	.477	.442	6714.11
5	.485	3.000	.493	.460	6714.11
6	.499	3.005	.507	.476	6672.50
7	.500	3.111	.507	.476	5791.76
8	.494	3.326	.501	.470	4008.21
9	.663	3.587	.665	.658	1838.42
10	.621	3.851	.622	.617	354.96
11	.575	4.115	.576	.572	2548.35
12	.525	4.379	.526	.522	4741.73
13	.470	4.643	.470	.466	6935.11
14	.409	4.907	.410	.404	9128.50
15	.398	5.171	.397	.404	11321.88
16	.386	5.435	.383	.404	13515.27
17	.372	5.718	.367	.404	15859.88
18	.356	6.000	.348	.404	18204.50

TRIAL A

TABLE NO. 2 (CONT.)

HISTORY OF THICKNESS REFINEMENT

CYCLE NO. 1 SUB-CYCLE NO.10

NO.	REFINED PLATE	WEIGHTING FUNCTION	OLD PLATE	REQ'D PLATE	PRIMARY STRESS
1	.605	3.000	.608	.594	6741.05
2	.426	3.000	.434	.405	6741.05
3	.445	3.000	.451	.424	6741.05
4	.462	3.000	.468	.443	6741.05
5	.479	3.000	.485	.460	6741.05
6	.494	3.005	.499	.476	669 #.48
7	.494	3.111	.500	.476	5819.78
8	.489	3.326	.494	.471	4038.33
9	.662	3.587	.663	.657	1871.09
10	.620	3.851	.621	.616	319.71
11	.575	4.115	.575	.571	2510.52
12	.525	4.379	.525	.522	4701.32
13	.469	4.643	.470	.465	6892.12
14	.408	4.907	.409	.404	9082.93
15	.399	5.171	.398	.404	11273.73
16	.389	5.435	.386	.404	13464.54
17	.377	5.718	.372	.404	15806.39
18	.363	6.000	.356	.404	18148.25

TRIAL A
TABLE NO. 2 (CONT.)

increase in the bottom stress, but little change in the neutral axis region. Therefore if any plate, say the keel plate, is too thick, the primary stress acting on it is small, the resulting allowable tertiary stress is liberal, and the plate is made thinner. As the keel plate becomes thinner, the allowable tertiary stress becomes less liberal, and the required thicknesses slowly increase. This is exactly what happens in Trial A of Table 2.

The distribution of thicknesses of Trial B is very different from that of Trial A. The plate thicknesses increase up the side shell, and the total cross sectional area is excessive. However, the refinement changes the thicknesses to meet a required distribution very similar to that of Trial A. Thicknesses at the bottom must be increased while those at the top must be decreased. Again the stress distribution changes, but the neutral axis variation is small, and the scantlings vary according to the theory discussed above. For the keel plate, the variation is in the direction of increasing thickness. But the thicknesses of the top plates are being decreased at a faster rate than the bottom plates are being increased, hence the total cross sectional area becomes less. Since the neutral axis variation is small, the overall stress distribution increases which also increases the required thicknesses. At the bottom, the keel plate thickness is being increased, but the required thickness also becomes greater which seems to prevent convergence. However, the increase in plate thickness is far more rapid than the rate of required thickness increase. Comparison of the trend of Trial A with that of Trial B

INITIAL THICKNESS SELECTION

NO.	PLATE THICKNESS
1	.400
2	.400
3	.400
4	.400
5	.400
6	.401
7	.422
8	.464
9	.515
10	.567
11	.619
12	.670
13	.722
14	.774
15	.826
16	.877
17	.933
18	.988

TRIAL B
TABLE NO. 2

HISTORY OF THICKNESS REFINEMENT

CYCLE NO. 1 SUB-CYCLE NO. 1

NO.	REFINED PLATE	WEIGHTING FUNCTION	OLD PLATE	REQ'D PLATE	PRIMARY STRESS
1	.440	3.500	.400	.579	5509.39
2	.399	3.500	.400	.394	5509.39
3	.403	3.500	.400	.413	5509.39
4	.407	3.500	.400	.431	5509.39
5	.411	3.500	.400	.448	5509.39
6	.415	3.500	.401	.464	5486.33
7	.431	3.500	.422	.464	4998.05
8	.464	3.500	.464	.462	4009.27
9	.532	3.500	.515	.589	2806.36
10	.564	3.500	.567	.553	1590.37
11	.595	3.500	.619	.514	374.38
12	.626	3.500	.670	.471	841.61
13	.655	3.500	.722	.421	2057.60
14	.692	3.500	.774	.404	3273.59
15	.732	3.500	.826	.404	4489.58
16	.772	3.500	.877	.404	5705.57
17	.815	3.500	.933	.404	7005.40
18	.858	3.500	.988	.404	8305.23

TRIAL B

TABLE NO. 2 (CONT.)

HISTORY OF THICKNESS REFINEMENT

CYCLE NO. 1 SUB-CYCLE NO. 2

NO.	REFINED PLATE	WEIGHTING FUNCTION	OLD PLATE	REQ'D PLATE	PRIMARY STRESS
1	.472	3.500	.440	.584	5949.91
2	.399	3.500	.399	.398	5949.91
3	.406	3.500	.403	.417	5949.91
4	.413	3.500	.407	.435	5949.91
5	.420	3.500	.411	.452	5949.91
6	.427	3.500	.415	.468	5923.34
7	.439	3.500	.431	.468	5360.86
8	.464	3.500	.464	.466	4221.80
9	.546	3.500	.532	.598	2836.07
10	.563	3.500	.564	.562	1435.27
11	.579	3.500	.595	.522	34.47
12	.593	3.500	.626	.477	1366.33
13	.604	3.500	.655	.427	2767.12
14	.628	3.500	.692	.404	4167.92
15	.659	3.500	.732	.404	5568.72
16	.690	3.500	.772	.404	6989.52
17	.724	3.500	.815	.404	8466.90
18	.757	3.500	.858	.404	9964.28

TRIAL B
TABLE NO. 2 (CONT.)

HISTORY OF THICKNESS REFINEMENT

CYCLE NO. 1 SUB-CYCLE NO. 3

NO.	REFINED PLATE	WEIGHTING FUNCTION	OLD PLATE	REQ'D PLATE	PRIMARY STRESS
1	.497	3.500	.472	.585	5984.73
2	.398	3.500	.399	.398	5984.73
3	.408	3.500	.406	.417	5984.73
4	.418	3.500	.413	.435	5984.73
5	.427	3.500	.420	.453	5984.73
6	.436	3.500	.427	.469	5956.20
7	.446	3.500	.439	.469	5352.26
8	.465	3.500	.464	.466	4129.24
9	.560	3.500	.546	.606	2641.37
10	.564	3.500	.563	.568	1137.32
11	.568	3.500	.579	.528	366.73
12	.568	3.500	.593	.483	1870.78
13	.566	3.500	.604	.432	3374.83
14	.578	3.500	.628	.404	4878.89
15	.602	3.500	.659	.404	6382.94
16	.627	3.500	.690	.404	7886.99
17	.653	3.500	.724	.404	9494.74
18	.679	3.500	.757	.404	11102.49

TRIAL B

TABLE NO. 2 (CONT.)

HISTORY OF THICKNESS REFINEMENT

CYCLE NO. 1 SUB-CYCLE NO. 4

NO.	REFINED PLATE	WEIGHTING FUNCTION	OLD PLATE	REQ'D PLATE	PRIMARY STRESS
1	.517	3.500	.497	.586	6055.45
2	.399	3.500	.398	.399	6055.45
3	.411	3.500	.408	.418	6055.45
4	.422	3.500	.418	.436	6055.45
5	.433	3.500	.427	.453	6055.45
6	.443	3.500	.436	.469	6024.96
7	.451	3.500	.446	.469	5379.57
8	.465	3.500	.465	.466	4072.63
9	.571	3.500	.560	.613	2482.66
10	.567	3.500	.564	.575	875.40
11	.560	3.500	.568	.534	731.86
12	.551	3.500	.568	.488	2339.12
13	.537	3.500	.566	.436	3946.38
14	.540	3.500	.578	.404	5553.64
15	.558	3.500	.602	.404	7160.90
16	.577	3.500	.627	.404	8768.16
17	.598	3.500	.653	.404	10486.24
18	.618	3.500	.679	.404	12204.32

TRIAL B

TABLE NO. 2 (CONT.)

HISTORY OF THICKNESS REFINEMENT

CYCLE NO. 1 SUB-CYCLE NO. 5

NO.	REFINED PLATE	WEIGHTING FUNCTION	OLD PLATE	REQ'D PLATE	PRIMARY STRESS
1	.532	3.500	.517	.586	6112.81
2	.399	3.500	.399	.399	6112.81
3	.412	3.500	.411	.418	6112.81
4	.425	3.500	.422	.437	6112.81
5	.438	3.500	.433	.454	6112.81
6	.449	3.500	.443	.470	6080.57
7	.455	3.500	.451	.470	5398.14
8	.465	3.500	.465	.466	4016.18
9	.582	3.500	.571	.620	2334.94
10	.570	3.500	.567	.581	635.42
11	.556	3.500	.560	.540	1064.10
12	.538	3.500	.551	.493	2763.62
13	.516	3.500	.537	.441	4463.14
14	.509	3.500	.540	.404	6162.66
15	.524	3.500	.558	.404	7862.18
16	.539	3.500	.577	.404	9561.69
17	.555	3.500	.598	.404	11378.39
18	.570	3.500	.618	.404	13195.09

TRIAL B

TABLE NO. 2 (CONT.)

HISTORY OF THICKNESS REFINEMENT

CYCLE NO. 1 SUB-CYCLE NO. 6

NO.	REFINED PLATE	WEIGHTING FUNCTION	OLD PLATE	REQ'D PLATE	PRIMARY STRESS
1	.544	3.500	.532	.587	6177.05
2	.399	3.500	.399	.400	6177.05
3	.414	3.500	.412	.419	6177.05
4	.428	3.500	.425	.437	6177.05
5	.441	3.500	.438	.455	6177.05
6	.454	3.500	.449	.471	6143.08
7	.459	3.500	.455	.471	5424.13
8	.466	3.500	.465	.467	3968.22
9	.592	3.500	.582	.627	2197.03
10	.574	3.500	.570	.588	406.58
11	.553	3.500	.556	.545	1383.88
12	.529	3.500	.538	.499	3174.33
13	.500	3.500	.516	.445	4964.78
14	.486	3.500	.509	.404	6755.24
15	.498	3.500	.524	.404	8545.69
16	.509	3.500	.539	.404	10336.15
17	.521	3.500	.555	.404	12250.05
18	.534	3.500	.570	.404	14163.95

TRIAL B
TABLE NO. 2 (CONT.)

HISTORY OF THICKNESS REFINEMENT

CYCLE NO. 1 SUB-CYCLE NO. 7

NO.	REFINED PLATE	WEIGHTING FUNCTION	OLD PLATE	REQ'D PLATE	PRIMARY STRESS
1	.554	3.500	.544	.589	6291.93
2	.399	3.500	.399	.401	6291.93
3	.415	3.500	.414	.420	6291.93
4	.430	3.500	.428	.438	6291.93
5	.445	3.500	.441	.456	6291.93
6	.458	3.500	.454	.472	6256.33
7	.462	3.500	.459	.472	5502.86
8	.466	3.500	.466	.467	3977.05
9	.601	3.500	.592	.633	2120.82
10	.578	3.500	.574	.593	244.40
11	.553	3.500	.553	.551	1632.02
12	.523	3.500	.529	.503	3508.44
13	.489	3.500	.500	.449	5384.86
14	.468	3.500	.486	.404	7261.28
15	.477	3.500	.498	.404	9137.70
16	.486	3.500	.509	.404	11014.12
17	.495	3.500	.521	.404	13019.92
18	.505	3.500	.534	.404	15025.72

TRIAL B
TABLE NO. 2 (CONT.)

HISTORY OF THICKNESS REFINEMENT

CYCLE NO. 1 SUB-CYCLE NO. 8

NO.	REFINED PLATE	WEIGHTING FUNCTION	OLD PLATE	REQ'D PLATE	PRIMARY STRESS
1	.562	3.500	.554	.590	6420.62
2	.400	3.500	.399	.402	6420.62
3	.417	3.500	.415	.421	6420.62
4	.432	3.500	.430	.439	6420.62
5	.447	3.500	.445	.457	6420.62
6	.461	3.500	.458	.473	6383.63
7	.464	3.500	.462	.473	5600.73
8	.467	3.500	.466	.468	4015.31
9	.609	3.500	.601	.638	2086.55
10	.583	3.500	.578	.598	136.83
11	.553	3.500	.553	.555	1812.90
12	.520	3.500	.523	.507	3762.63
13	.481	3.500	.489	.453	5712.36
14	.454	3.500	.468	.404	7662.09
15	.461	3.500	.477	.404	9611.81
16	.468	3.500	.486	.404	11561.54
17	.475	3.500	.495	.404	13645.70
18	.482	3.500	.505	.404	15729.86

TRIAL B
TABLE NO. 2 (CONT.)

shows that both are converging toward the same thickness distribution. In particular, both trials seem to be converging upon a keel plate thickness of about 0.595 inches.

The iteration has been terminated short of the final required scantlings because of the large number of iterations necessary. The trend is obvious in both cases and further iterations would not cause convergence within a reasonable time limit because of the retardation caused by the weighting functions. A slight modification to Eq. (55) would result in a more rapid convergence.

Rather than modify the existing weighting function valves for a more rapid convergence, a more reasonable initial thickness selection can be chosen than that used in Trial A or B. In the present synthesis, the initial thicknesses are selected so as to reduce the computation time to a minimum and yet attain convergence. Except for small ships, the limiting primary stress requirement prevails and longitudinal strength members are designed to satisfy this restriction. Therefore, by assuming a bending stress distribution equal to the limiting primary stress at the top fibers of the hull girder, and assuming a neutral axis location at .4 x depth above the keel, the initial plate thicknesses for rapid convergence may be chosen as those required under the resulting allowable tertiary stress. The longitudinal stiffener scantlings are calculated according to the allowed secondary bending stress resulting from the initial primary stress distribution. These thicknesses in no way prejudice the results since any other stress distribution may be selected. However, the number of iterations is considerably reduced because the orientation of the thicknesses is now defined and only the correct magnitudes need to be determined.

Trial C of Table 2 demonstrates the savings in computation time when the initial limiting stress distribution method is assumed. The initial thicknesses are already properly selected and some plates even match the required thicknesses. After four iterations, the thicknesses are within 0.026 inches of the required values for all plates. The required values in Trial C are found to be nearly the same as those in Trials A and B.

As mentioned earlier in this discussion, the strong possibility exists that when examining large shallow ships, a negative tertiary stress may result in the refinement iteration. The weighting function insures that this will not be a random occurrence, but will arise only if the thicknesses required under lateral loads are so small that as the plates are refined, the total hull cross section fails to provide an adequate section modulus to resist the bending stress. To prevent a breakdown of the solution, the refinement process must be terminated. A running check is kept of each stress schedule as the refinement progresses. If any primary stress exceeds a safe margin, the refinement is stopped and the process moves to linear extrapolation. Halting the refinement when the primary stress became greater than $S_y/1.35$ was found to be a sufficient factor of safety for the program operation. However, termination of the refinement prematurely results in a ship

INITIAL THICKNESS SELECTION

NO.	PLATE THICKNESS
1	.676
2	.461
3	.483
4	.504
5	.524
6	.542
7	.542
8	.530
9	.557
10	.524
11	.487
12	.447
13	.404
14	.404
15	.404
16	.404
17	.404
18	.404

TRIAL C

TABLE NO. 2

HISTORY OF THICKNESS REFINEMENT

CYCLE NO. 1 SUB-CYCLE NO. 1

NO.	REFINED PLATE	WEIGHTING FUNCTION	OLD PLATE	REQ'D PLATE	PRIMARY STRESS
1	.654	3.000	.676	.587	6179.34
2	.446	3.000	.461	.400	6179.34
3	.467	3.000	.483	.419	6179.34
4	.487	3.000	.504	.437	6179.34
5	.506	3.000	.524	.455	6179.34
6	.524	3.005	.542	.470	6138.66
7	.524	3.111	.542	.470	5277.63
8	.515	3.326	.530	.465	3534.00
9	.580	3.587	.557	.660	1412.77
10	.543	3.851	.524	.618	731.53
11	.504	4.115	.487	.573	2875.83
12	.461	4.379	.447	.524	5020.13
13	.415	4.643	.404	.467	7164.42
14	.404	4.907	.404	.404	9308.72
15	.404	5.171	.404	.404	11453.02
16	.404	5.435	.404	.404	13597.32
17	.404	5.718	.404	.404	15889.46
18	.404	6.000	.404	.404	18181.61

TRIAL C
TABLE NO. 2 (CONT.)

HISTORY OF THICKNESS REFINEMENT

CYCLE NO. 1 SUB-CYCLE NO. 2

NO.	REFINED PLATE	WEIGHTING FUNCTION	OLD PLATE	REQ'D PLATE	PRIMARY STRESS
1	.639	3.000	.654	.593	6596.48
2	.435	3.000	.446	.404	6596.48
3	.456	3.000	.467	.423	6596.48
4	.476	3.000	.487	.441	6596.48
5	.495	3.000	.506	.459	6596.48
6	.512	3.005	.524	.475	6555.67
7	.512	3.111	.524	.475	5691.78
8	.504	3.326	.515	.469	3942.36
9	.596	3.587	.580	.655	1814.10
10	.558	3.851	.543	.614	337.31
11	.517	4.115	.504	.569	2488.72
12	.472	4.379	.461	.520	4640.13
13	.424	4.643	.415	.464	6791.54
14	.404	4.907	.404	.404	8942.95
15	.404	5.171	.404	.404	11094.36
16	.404	5.435	.404	.404	13245.77
17	.404	5.718	.404	.404	15545.52
18	.404	6.000	.404	.404	17845.26

TRIAL C
TABLE NO. 2 (CONT.)

HISTORY OF THICKNESS REFINEMENT

CYCLE NO. 1 SUB-CYCLE NO. 3

NO.	REFINED PLATE	WEIGHTING FUNCTION	OLD PLATE	REQ'D PLATE	PRIMARY STRESS
1	.627	3.000	.639	.593	6624.00
2	.427	3.000	.435	.404	6624.00
3	.448	3.000	.456	.423	6624.00
4	.467	3.000	.476	.441	6624.00
5	.486	3.000	.495	.459	6624.00
6	.503	3.005	.512	.475	6582.95
7	.503	3.111	.512	.475	5714.23
8	.496	3.326	.504	.470	3955.02
9	.609	3.587	.596	.656	1814.85
10	.570	3.851	.558	.615	348.60
11	.527	4.115	.517	.570	2512.05
12	.481	4.379	.472	.521	4675.50
13	.431	4.643	.424	.464	6838.95
14	.404	4.907	.404	.404	9002.40
15	.404	5.171	.404	.404	11165.85
16	.404	5.435	.404	.404	13329.30
17	.404	5.718	.404	.404	15641.92
18	.404	6.000	.404	.404	17954.54

TRIAL C
TABLE NO. 2 (CONT.)

HISTORY OF THICKNESS REFINEMENT

CYCLE NO. 1 SUB-CYCLE NO 4

NO.	REFINED PLATE	WEIGHTING FUNCTION	OLD PLATE	REQ'D PLATE	PRIMARY STRESS
1	.619	3.000	.627	.593	6667.37
2	.422	3.000	.427	.404	6667.37
3	.442	3.000	.448	.424	6667.37
4	.461	3.000	.467	.442	6667.37
5	.479	3.000	.486	.460	6667.37
6	.496	3.005	.503	.476	6626.33
7	.497	3.111	.503	.476	5757.66
8	.490	3.326	.496	.470	3998.57
9	.619	3.587	.609	.655	1858.53
10	.579	3.851	.570	.614	304.78
11	.536	4.115	.527	.570	2468.09
12	.488	4.379	.481	.520	4631.40
13	.437	4.643	.431	.464	6794.71
14	.404	4.907	.404	.404	8958.02
15	.404	5.171	.404	.404	11121.33
16	.404	5.435	.404	.404	13284.64
17	.404	5.718	.404	.404	15597.11
18	.404	6.000	.404	.404	17909.58

TRIAL C
TABLE NO. 2 (CONT.)

cross section which is too large to satisfy the least weight requirement under lateral loading, but too small to resist bending. The linear program will add material to the outer fibers of the hull in an attempt to satisfy the bending strength requirements. But as previously demonstrated, when the deficiency in primary stress satisfaction is large, the increase of material by the linear program falls short of lowering the stress adequately. Therefore, another design cycle is required and further refinement under normal load is made. The problem of negative tertiary stresses is not likely to arise because the added material at the outer fibers lowers the primary stress enough to allow reduction of plate thicknesses near the neutral axis. But, if this reduction again causes the primary stresses to become greater than $S_y/1.35$, the refinement is again terminated and the process repeats itself until the material is distributed in the optimum manner.

On small ships, the cross sectional area required under normal loads generally exceeds that necessary to resist primary bending, so that the above problem is not encountered.

The preceding discussion attempts to show analytically that the initial thickness selection is independent of the final solution scantlings. Any attempts at a mathematical proof would be extremely difficult, if not impossible, because of the complicated nonlinear relationships involved.

CHAPTER VIII

DISCUSSION OF STIFFENER SELECTION

Table 2 of the ABS Rules lists the scantlings of longitudinals and beams as a function of N & L. For longitudinally framed cargo ships, only the bottom, inner bottom, and deck longitudinals are covered by the Rules. Equation (54) restated here:

$$Z_{ABS} = \frac{NL^2}{240}$$

where:

Z_{ABS} = section modulus of the plate-stiffener combination

$N = F_i \cdot h_i \cdot C$

L = web spacing

C = constant defined in Ref. (10)

is used for the side longitudinals. This is also the formula used to determine the scantlings of longitudinals on bulk carriers which have an inner bottom and are longitudinally framed.

The relationship between Eq. (54) and the values of Table 2 have been investigated in order to justify use of this equation in the synthesis. Rather than confine the analysis to any specific stiffener location, the hull section modulus from Table 2 is compared against Eq. (54) as a function of N and L.

An associated plating thickness for the combined beam is assumed as being equal to the thickness of stiffener flanges. In order to determine a required section modulus for a plate stiffener combination, some assumptions for effective plate breadth and plate thickness must be made. No plate is specified when determining the necessary stiffener in Table 2; only the water head and frame spacing. This analysis will assume an effective plate breadth of 60 times the thickness, and a thickness equal to the thickness of the stiffener flange. Therefore, a plate is specified for the study, and although no real logic can back up this assumption of thickness, some correspondence exists between the range of stiffener flange thicknesses which vary from 0.25" to 0.5", and the range of ABS plate thicknesses which vary from 0.27" to 1.14".

Ref. (1) concludes that ABS uses an effective breadth equal to 30 times the plate thickness. Although no plate is specified, the result of assuming 60 times the thickness of the flange will cover all the plate thickness ranges included under the Rules, and the total plate area will match the thickness range covered if the Rules do assume 30 times thickness of plate for effective breadth. The advantage of the plan described above is that, for the purposes of stiffener analysis, a plate is defined to be proportional to stiffener size, which is the usual situation. A comparison of section modulus values from Table 2 using the above assumptions, and the modulus required by Eq. (54) are plotted in Fig. 9. . Values from Eq. (54) are plotted against Table 2 section modulii under the assumption of plating breadths equal to both 60 times the thickness and 30 times the

LONGITUDINALS

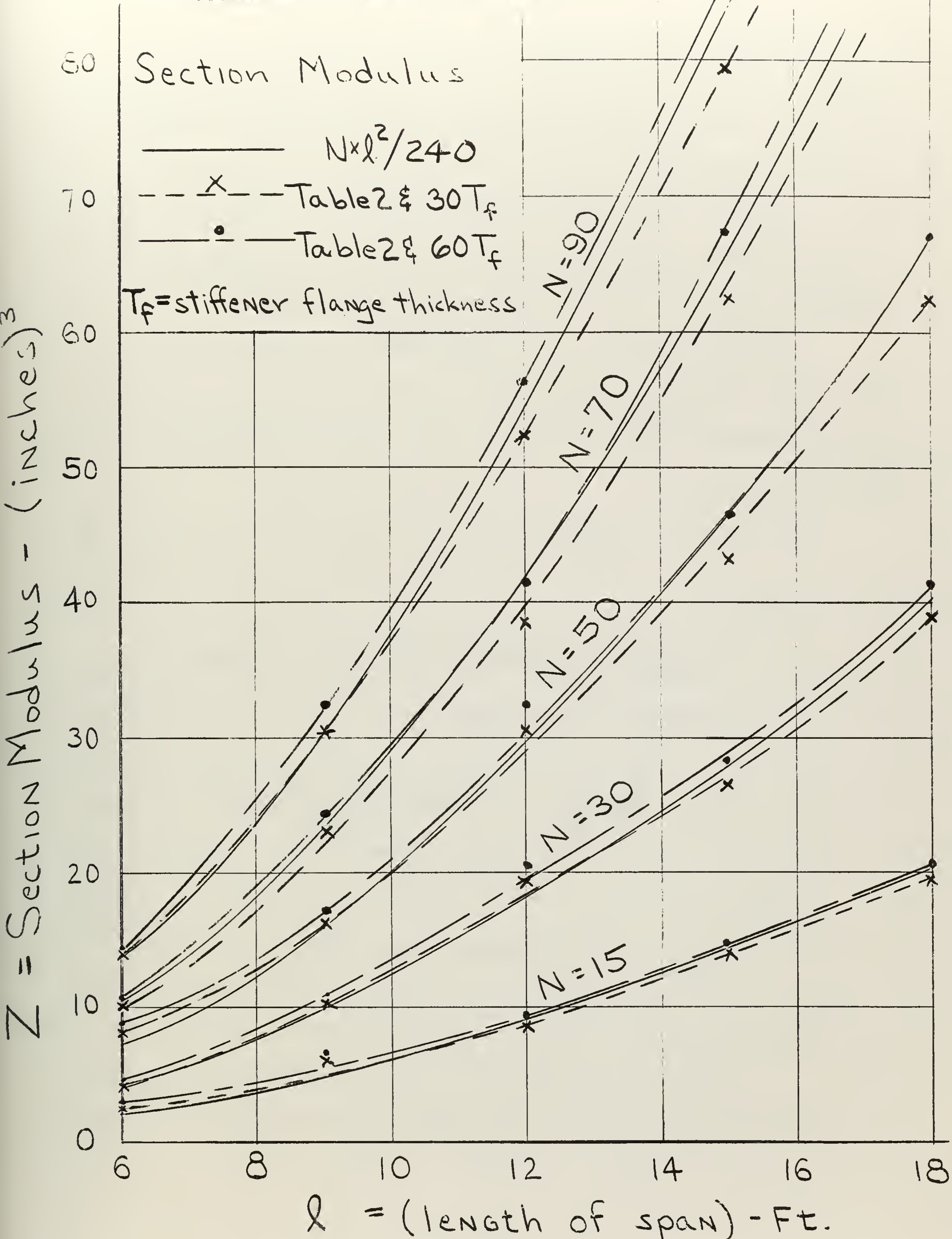


FIG. 9

thickness. Since the section modulus values for various values of N are within 8 percent, the conclusion must be that the section modulus is relatively insensitive to plating area variation. So, even though an exact plate size is not specified by the Rules, liberal variation of plating thicknesses can be associated with the Table 2 stiffeners, showing that the Table is in good agreement with Equation (54).

With the assurance that Eq. (54) represents ABS standards, these requirements are analysed under the actual loads imposed upon the longitudinals. The equation itself may be derived from simple beam theory as follows:

$$M = \frac{q\, L^2}{K} \quad (\text{lb - ft})$$

where,

K = function of boundary conditions (for clamped beams, $K = 12$)

$q = F \cdot h \cdot 64.$ (lb/ft)

$$Z = \frac{M_o \cdot 12}{(S_2)_{all}} = \frac{(F \cdot h \cdot 64 \cdot L^2 \cdot 12)}{K \cdot (S_2)_{all}} \tag{63}$$

and

$(S_2)_{all}$ = allowed girder bending stress

Z = required section modulus

Now the above Equation (63) is related to the relationship defining Z in formula (54) by;

$$\frac{NL^2}{240} = \frac{F \cdot h \cdot 64 \cdot L^2 \cdot 12}{K \cdot (S_2)_{all}} \tag{64}$$

The right side of Eq. (64) may be modified as,

$$\frac{N \cdot L^2}{C_1} \cdot \frac{64 \cdot 12}{K \cdot (S_2)_{all}}$$

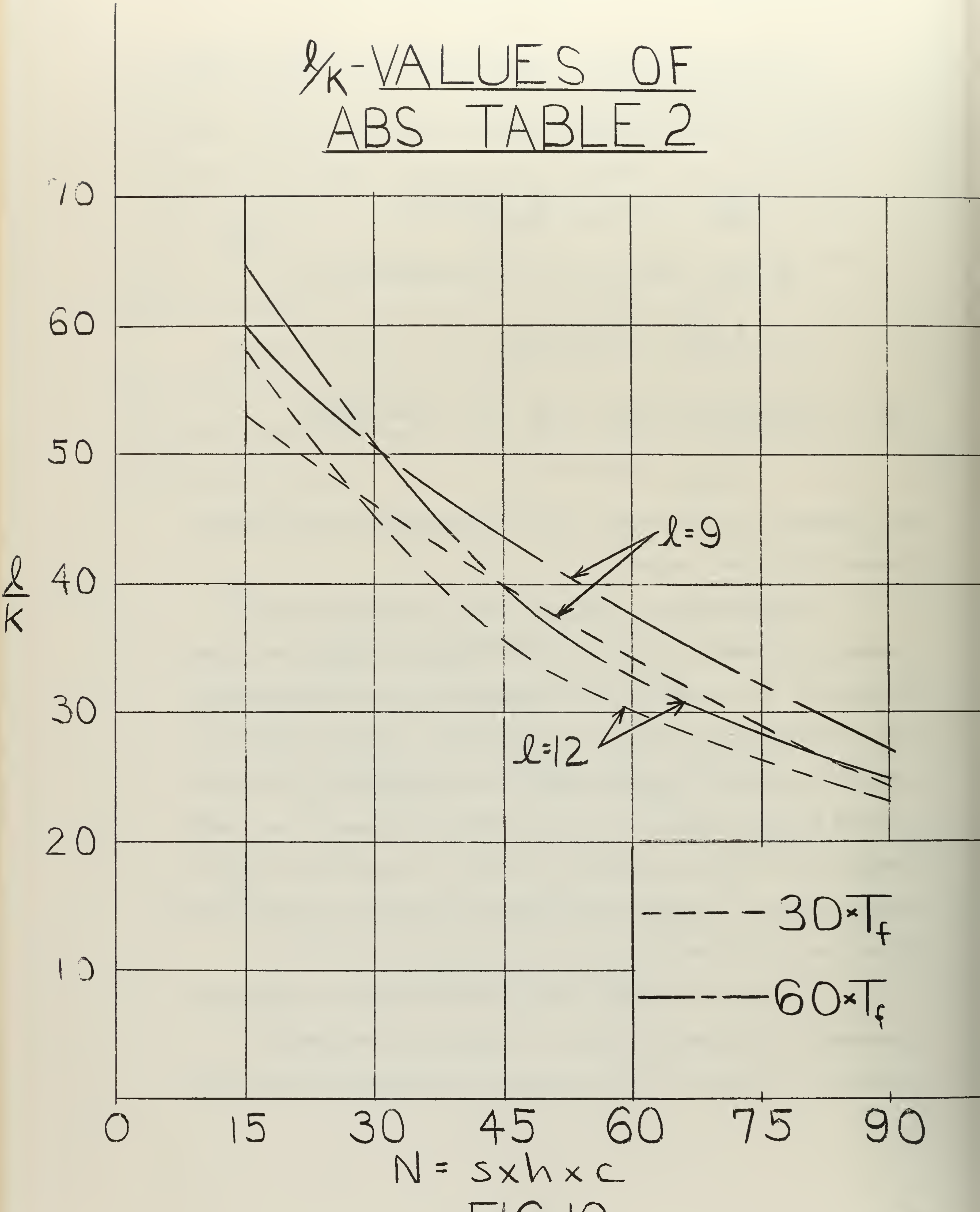
but C_1 is approximately equal to $\frac{12}{K}$ so, Eq. (64) becomes

$$(S_2)_{all} = 15{,}400 \text{ P.S.I.}$$

and therefore; the ABS seems to allow a constant allowable bending stress for all ship length.

The ABS seems to derive stiffener scantlings based on bending requirements only; and instability is not considered in the derivation. But, under the same assumptions of associated plating for the stiffeners in Table 2 as stated above, certain slenderness ratios are implied. As seen in Fig. 10, the implied $^L/_k$ ratios are plotted for two values of web spacing which are common to most ship lengths. The results are somewhat similar to known Naval practice which requires a $^L/_k$ that varies linearly from 30 at the base line to 55 at the strength deck.

Table 3 is a sample iteration in the computer program for designing a stiffener according to the procedure described in Section 3 of Chapter IV. This example is a hypothetical case for a



l/K-VALUES OF
ABS TABLE 2
70
60
50
40
30
20
10
l/K
0
15
30
45
60
75
90
N = s x h x c
l=9
l=12
30×T_f
60×T_f

FIG.10

stiffener under a large normal load and a compressive stress of 18,778.66 psi. Assuming that ABS requires a section modulus of 9.23 cubic inches for the plate stiffener combination, the resulting stiffener proportionality constant is 0.48. The stiffener scantling corresponding to this proportionality constant, together with its associated plating, yields an $^{L}/_{k}$ ratio of 66.06. But the Timoshenko formula, Eq. (51), requires a section modulus of 89.29 cubic inches to prevent buckling. The average value of the initially assumed section modulus value and that finally required is used in the second iteration. The resulting stiffener immediately yields a smaller $^{L}/_{k}$ value, and consequently a more liberal required section modulus. The rather small decrease in Z required by Timoshenko's formula is explained by the fact that the magnification factor in Eq. (51) is governed by the large compressive stress on the composite beam. As the iteration proceeds, a stiffener is found which satisfies the buckling criteria. Table 3 is only an example to show the technique of converging on the required stiffener scantling, as explained in Section 3 of Chapter IV.

The Rules are indefinite regarding section modulus requirements for the wide range of ship configurations envisioned in this design. Many mathematical expressions may be derived for specific framing systems, but none has het been developed for a general system of framing. The incompletely stated ABS standards for combination framed ships forces reliance upon rational mechanics methods, rather than extrapolation of the Rules which may be unreliable for the system

TYPICAL ITERATION FOR STIFFENER SCANTLINGS

BASIC STIFFENER	9.00X 7.04X.751 T
PLATE THICKNESS	.461 INCHES
A.B.S. REQUIRED Z	9.23 CU. IN.
WEB SPACING	10.00 FT.
COMP. STRESS	18778.66 PSI

PROPORTIONALITY CONSTANT	ASSUMED Z	L/K	Z REQUIRED BY TIMOSHENKO
.48	9.23	66.06	89.29
.99	49.26	30.49	85.98
1.08	67.62	28.36	85.87
1.11	76.74	27.67	85.83
1.13	81.29	27.36	85.82
1.14	83.55	27.21	85.81
1.14	84.68	27.14	85.80
1.14	85.24	27.10	85.80

TABLE NO. 3

of framing being investigated. The criteria for stiffener design is set to the most severe requirements of either Eq. (53) or (54). Therefore, an adequate plate-stiffener combination is insured. Further investigation is necessary to determine the feasibility of removing the ABS restriction and using a general formula based on rational structural derivation.

Use of sections based on the current basic stiffener may yield beams with depths larger than desired for practical usage, but by changing the geometric proportions of the basic stiffener, the same section modulus may be obtained with smaller depths.

The method used in the present design; to compromise between the section modulus required by ABS and by sound structural formulation, seems to be the best approach.

CHAPTER IX

Analysis and Applications

Discussion of Sample Results

For the purpose of demonstrating the flexibility of this program, the analysis of several ranges in ship length, breadth, or depth has been forsaken in favor of varying the internal configuration of a ship whose hull dimensions are constant. Much work remains; therefore, the following comparisons are only an indication of the analyses possible using this program.

No attempt will be made to search for a ship which is of minimum total weight since realistic judgments cannot be made based only on the longitudinally effective structure. The obvious result is that a transversely framed ship has the least continuous material, but its weight is augmented to a large extent by the transverse beams. As more sections are longitudinally framed, the longitudinally continuous material weight increases, but the decrease in the number of transverse webs compensates for this added weight. Since the present synthesis only considers longitudinal strength, a least weight analysis must await the design of primary transverse structure.

Appendix A is a typical design process for a transversely framed cargo ship of the "Mariner" type. Two combination framed ships of the same principal dimensions are shown in Appendix B and Appendix C to demonstrate the versatility of the synthesis. The plate scantlings of the transversely framed ship in Appendix A as determined from the

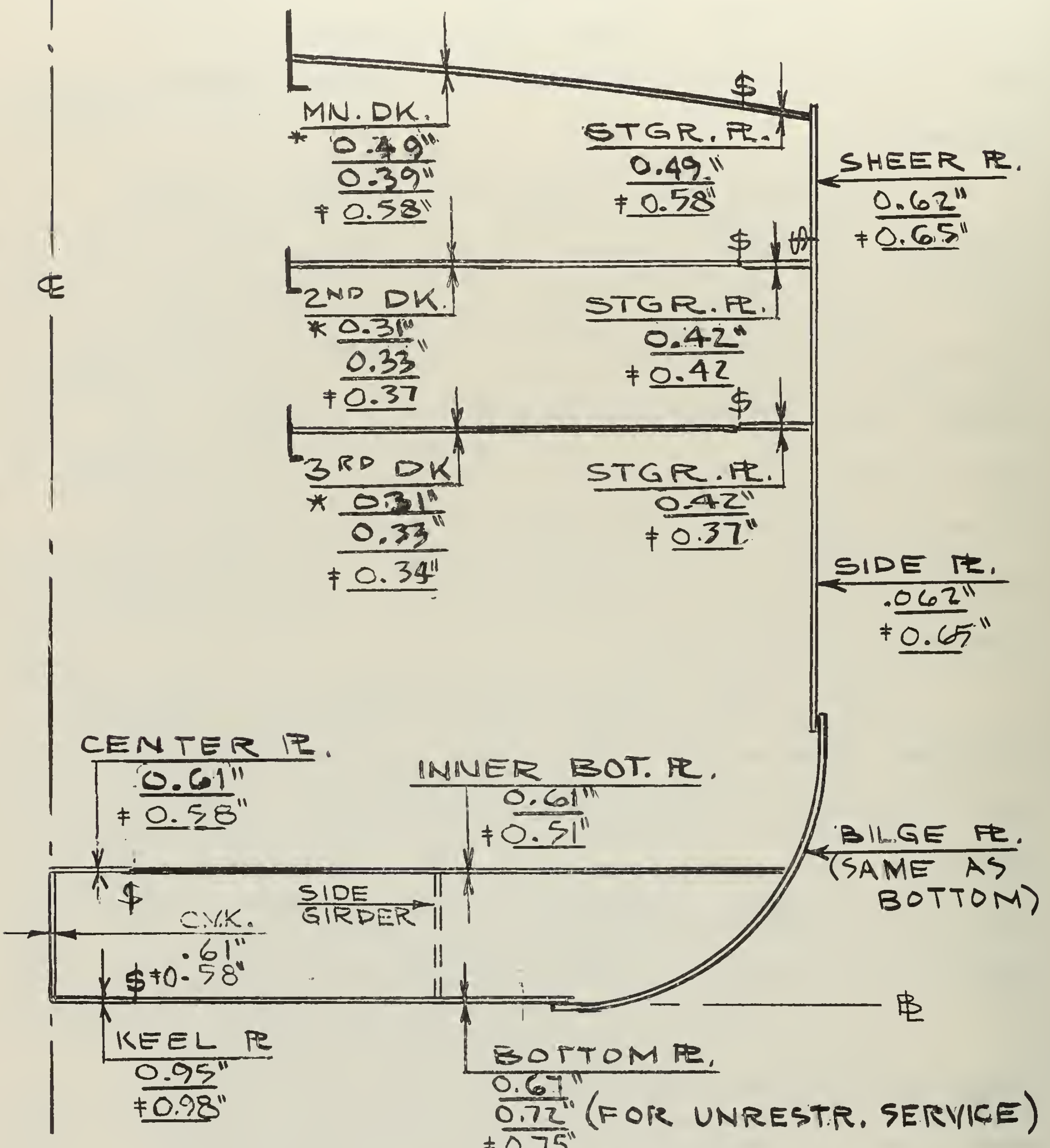
ABS Rules, Table 1, and the scantlings of a similar ship designed according to the process outlined in Refs. (8), (9), and (12), are shown in Fig. 11. These scantlings are to be compared with the results of Appendix A.

The computer program begins with a selection of initial scantlings as discussed in Chapter VII. The results of Cycle 1 show that although significant changes have been made in the original scantlings, the primary stress is still too high in both the "BENDING GOVERNS" (Cycle A) and "BUCKLING GOVERNS" (Cycle B) columns. The Cycle A column yields the current least weight solution, and although the buckling criteria is further from satisfaction, the use of this scantling set seems to be the best selection for initial thicknesses to be used in the next cycle.

Cycle 2 further refines the plate thicknesses, cutting down the primary stress and rearranging material to efficiently meet the stress requirements. This more efficient distribution results in a decrease in weight. Cycle A again yields the least weight solution with the best attempt at satisfaction of the primary stress. This column is again chosen as the initial thicknesses for Cycle 3.

The third cycle nearly satisfies all criteria. Both Cycles A and B practically meet the primary stress and section modulus restrictions. The weight is less in Cycle A, but since Cycle B satisfies the buckling strength restrictions, the final scantlings are selected from this column. Perhaps another iteration may have removed all deficiencies, but for demonstration purposes, the process is terminated.

A.B.S. PLATE THICKNESSES FOR TRIAL SHIP

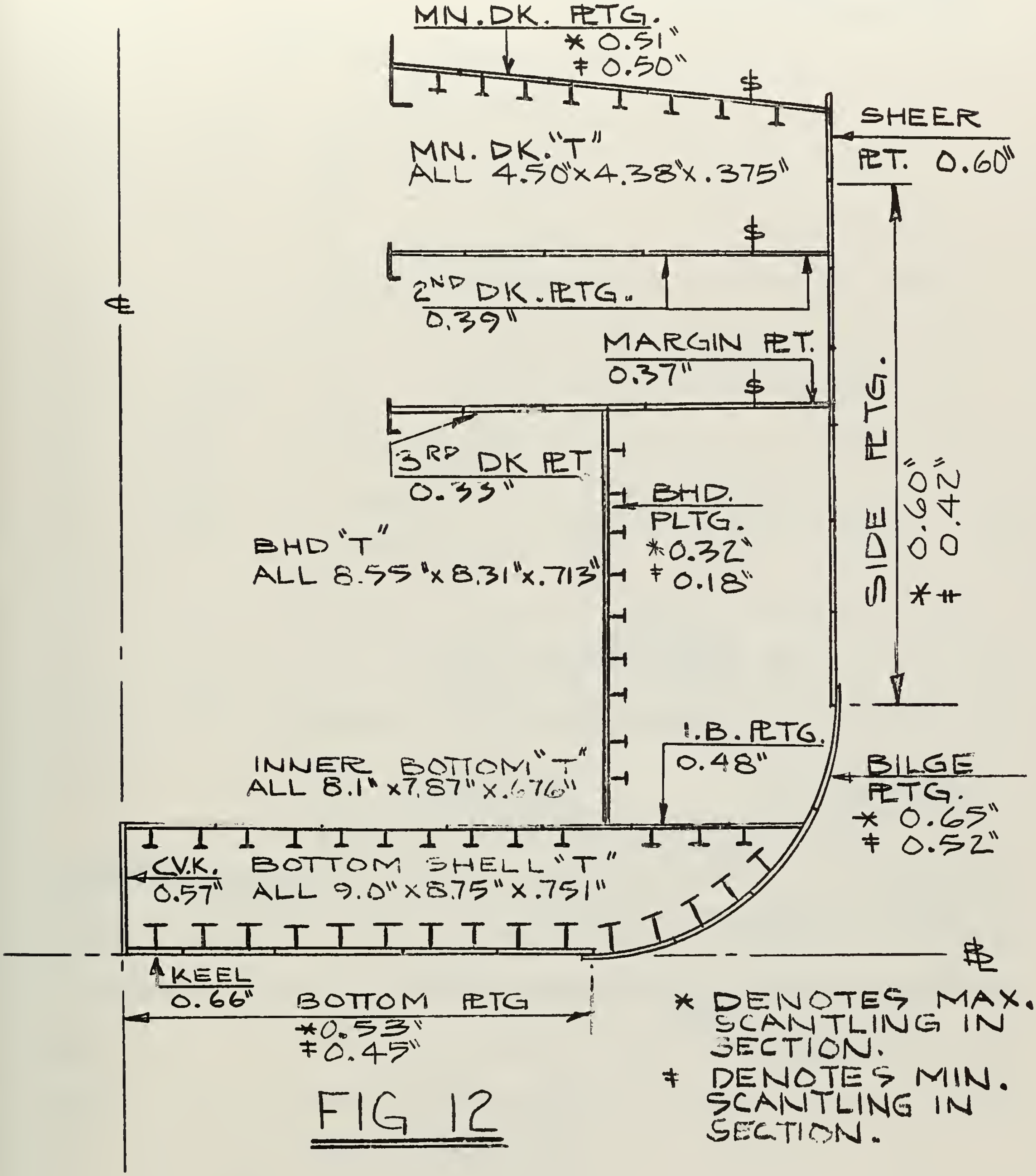


* DENOTES PLATES OVER LONGITUDINAL BEAMS

‡ SCANTLINGS FROM REF #12

FIG. 11

COMBINATION FRAMING SYSTEM
(SEE APPENDIX "B")



* DENOTES MAX. SCANTLING IN SECTION.

‡ DENOTES MIN. SCANTLING IN SECTION.

FIG 12

COMBINATION FRAMING SYSTEM
(SEE APPENDIX "B")

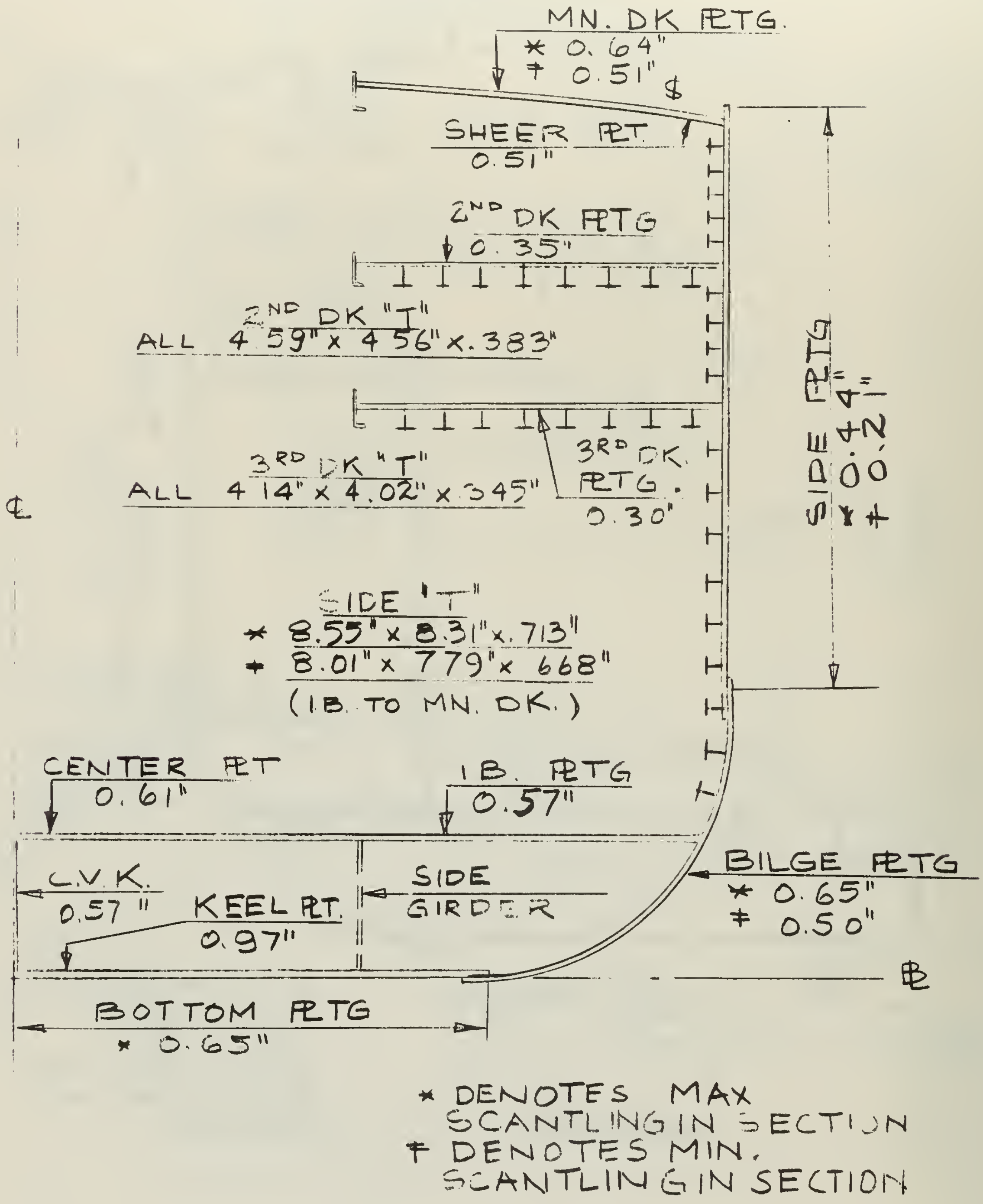


FIG. 13

The final scantlings, while not agreeing exactly with either ABS or Refs. (8), (9), and (12), in Fig. 11, closely approximate both cases within reasonable allowances. The principal discrepancy is in the main deck plating. The scantlings required by ABS do not reflect necessary section modulus considerations and are minimum values. Refs. (8), (9), and (12), consider section modulus requirements, but since the overall plating thicknesses in other locations are greater than the scantlings of the present synthesis, the requirements on the main deck are less severe. Other differences may be explained by the fact that this synthesis designs plates on an individual basis rather than on a gross panel basis, such as the "side" or "bottom" plate. Therefore, side plating for example, varies from 0.61" to 0.42" whereas the ABS would simply designate a constant thickness of 0.61". Except for variations explained by the methodology, the results of this synthesis are close enough to established values so that confidence can be placed in the program's effectiveness.

Recent developments in ship construction methods have incorporated combination framing arrangements similar to that shown in Appendix B. No evaluation can be made regarding the optimality of this arrangement as opposed to another system having perhaps the second deck and 'tween deck sections longitudinally framed. The results can not by checked completely with ABS Rule requirements since no provision is made for combination framing; but individual sections of Fig. 12 compare favorably with Fig. 11 when data does exist. All stiffener scantlings are reasonable, and in view of the method used in their selection, may be judged accurate. Some questions may arise regarding bulkhead plating thickness distribution. This bulkhead is regarded as longitudinally effective; therefore, the scantlings have been determined in the same manner as the other structural members, by the use of Equation (1).

Satisfaction of the total stress relationship yields a distribution of thicknesses shown in Fig. 12 rather than a distribution linearly decreasing from the bottom as would be the case if only lateral loading were considered.

The framing arrangement in Appendix C is created to portray the versatility of the program and is not necessarily a recommended design program. Here the orientation is just reversed from that in Appendix B; and in addition, the longitudinal bulkhead is deleted. All hull structure scantlings are in keeping with expected results.

This sample, together with the previously discussed results, are indications of the value this program will have in the examination of the advantages inherent in different framing systems.

Future Research

Future research should be directed towards achieving a synthesis which will completely design all structural members of a ship. Therefore, the first step would be to expand the existint program to include the design of primary transverse members. Any modifications to the present program to accomplish this would not alter the design logic since transverse members do not affect longitudinal strength.

The inclusion of transverse structures would then make an effective weight study possible, and a framing system analysis to determine the best orientation of framing based on least weight could also be made. Simultaneously, a longitudinal frame spacing study could be carried out to determine the optimum spacing.

Many of the formulations used have been selected only to arrive at reasonable scantlings. In some instances, the formulations do not necessarily comply with ABS Rules, or any governing body. Three separate synthesis should be created from the present program: One which designs an optimum least weight ship independent of existing codes, insofar as possible, and the other two to design ships which completely satisfy ABS and Naval criteria.

Before extending the scope of the design, the cycling procedure should be permanently set. The current need for interruption can be waived in favor of the alternate method described in Chapter IV.

Investigations should also be directed towards the determination of the most efficient use of available materials. The present design presumes mild steel to be used throughout the hull cross section. However, it may be conveniently adapted to handle different types of material since each plate panel is designed separately. The use of high strength steels can immediately be incorporated into the synthesis with only minor modifications.

The above proposals are only a few of the more important items which require immediate investigation. Satisfying these proposals, the synthesis would then provide a more complete approach to determine an optimum midship structural design.

Conclusions

This synthesis represents an attempt to develop a general, logical structural design process for the longitudinal continuous material of any internal hull configuration. Only through the use of high speed electronic computers was such a study possible. Otherwise, the numerous iterative processes required to satisfy the many strength requirements could not have been achieved.

Because the scope of this design is so large, verification of every possible internal configuration is impossible. Only by accumulating a library of data and then comparing this data against existing ships can the effectiveness of this synthesis be checked. Analysis of the sample configurations, however, does reveal that the synthesis is logically correct.

The method developed is not necessarily the best in all details, but it is believed to be an improvement over previous design programs and is flexible enough to provide rapid solutions for the structural design of any system of framing.

APPENDIX A

Transversely Framed

Cargo Ship

G E N E R A L C H A R A C T E R I S T I C S

LBP= 550.00,BREADTH= 75.00,DEPTH= 61.11,DRAFT= 27.50,HT. OF CVK= 6.11

NO. DECKS= 3,NO. BHDS= 0,FR.SP.= 30.00,WEB SPACING= 0

LONGITUDINALLY FRAMED EXCEPT AS NOTED BELOW

SECTION NO. 1 IS TRANSVERSELY FRAMED

SECTION NO. 2 IS TRANSVERSELY FRAMED

SECTION NO. 3 IS TRANSVERSELY FRAMED

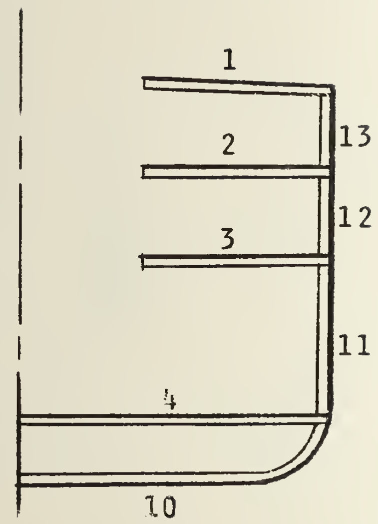
SECTION NO. 4 IS TRANSVERSELY FRAMED

SECTION NO.10 IS TRANSVERSELY FRAMED

SECTION NO.11 IS TRANSVERSELY FRAMED

SECTION NO.12 IS TRANSVERSELY FRAMED

SECTION NO.13 IS TRANSVERSELY FRAMED



MIDSHIP SECTION

RESULTS OF CYCLE NO. 1

	STARTING		BENDING GOVERNS		BUCKLING GOVERNS	
NO.	T	SIGMA1	T	SIGMA1	T	SIGMA1
	SHELL STRAKES					
1	1.050	12269.6	.996	12410.9	.996	12714.4
2	.730	12269.6	.671	12410.9	.671	12714.4
3	.730	12269.6	.671	12410.9	.671	12714.4
4	.730	12269.6	.671	12410.9	.671	12714.4
5	.730	12269.6	.671	12410.9	.671	12714.4
6	.730	12226.0	.671	12371.0	.671	12674.0
7	.730	11164.9	.672	11400.2	.672	11691.4
8	.730	8696.5	.674	9141.8	.674	9405.6
9	.656	5633.7	.664	6339.5	.664	6569.4
10	.623	2672.3	.625	3630.0	.625	3827.0
11	.586	289.2	.583	920.5	.583	1084.7
12	.543	3387.8	.534	1914.6	.534	1784.8
13	.504	6212.1	.486	4498.6	.486	4400.1
14	.504	9173.5	.452	7208.1	.452	7142.5
15	.504	12135.0	.454	9917.7	.570	9884.9
16	.504	15233.6	.455	12752.7	.572	12754.3
17	.504	18252.3	.578	15514.6	.573	15549.6
18	.504	21270.9	.579	18276.5	.575	18345.0

	DECK NO. 1					
19	.425	21503.7	.735	18489.4	.609	18560.5
20	.370	21641.1	.599	18615.2	.473	18687.8
21	.370	21774.2	.599	18736.9	.473	18811.0
22	.370	21878.6	.599	18832.5	.473	18907.7
23	.312	21969.8	.510	18913.2	.384	18989.4
	DECK NO. 2					
24	.382	16194.1	.335	13631.5	.451	13643.7
25	.382	16194.1	.335	13631.5	.451	13643.7
26	.382	16194.1	.335	13631.5	.451	13643.7
27	.382	16194.1	.335	13631.5	.451	13643.7
28	.382	16194.1	.335	13631.5	.451	13643.7
	DECK NO. 3					
29	.382	11117.3	.332	8986.6	.448	8942.5
30	.382	11117.3	.332	8986.6	.448	8942.5
31	.382	11117.3	.332	8986.6	.448	8942.5
32	.382	11117.3	.332	8986.6	.448	8942.5
33	.382	11117.3	.332	8986.6	.448	8942.5
	INNER BOTTOM STRAKES					
34	.689	8916.1	.629	9342.7	.629	9609.0
35	.660	8916.1	.598	9342.7	.598	9609.0
36	.660	8916.1	.598	9342.7	.598	9609.0
37	.660	8916.1	.598	9342.7	.598	9609.0
38	.660	8916.1	.598	9342.7	.598	9609.0
39	.660	8916.1	.598	9342.7	.598	9609.0
40	.660	8916.1	.598	9342.7	.598	9609.0
41	.660	8916.1	.598	9342.7	.598	9609.0

	BENDING	BUCKLING
WT. OF EFFECTIVE MATL	3.97 T/FT.	4.10 T/FT.
MAX. DIFF. IN BENDING STRESS (SIGMA1-LIMIT STRESS)	1204.1 PSI	1280.4 PSI
MAX. DIFF. IN BUCKLING STRESS (ACTUAL-ALLOWED)	7537.7 PSI	6268.9 PSI
N.A.(ABOVE KEEL)	24.72 FT.	25.02 FT.
SECTION MODULUS		
KEEL	61588.9 FT.SQ.IN.	60118.8 FT.SQ.IN.
DECK	40167.4 FT.SQ.IN.	40004.2 FT.SQ.IN.
LIMITING PRIMARY STRESS	17709.03 PSI	
REQUIRED SECTION MODULUS	43162.97FT.SQ.IN.	

TYPE:

1 TO CYCLE AGAIN WITH THICKNESS FROM BENDING
2 TO CYCLE AGAIN WITH THICKNESS FROM BUCKLING
3 TO STOP WITH THICKNESS FROM BENDING
4 TO STOP WITH THICKNESS FROM BUCKLING

1

RESULTS OF CYCLE NO. 2

	STARTING		BENDING GOVERNS		BUCKLING GOVERNS	
NO.	T	SIGMA1	T	SIGMA1	T	SIGMA1
	SHELL STRAKES					
1	.996	12410.9	.974	12364.8	.974	12555.3
2	.671	12410.9	.649	12364.8	.649	12555.3
3	.671	12410.9	.649	12364.8	.649	12555.3
4	.671	12410.9	.649	12364.8	.649	12555.3
5	.671	12410.9	.649	12364.8	.649	12555.3
6	.671	12371.0	.649	12326.3	.649	12516.6
7	.672	11400.2	.650	11390.3	.650	11574.0
8	.674	9141.8	.651	9213.0	.651	9381.3
9	.664	6339.5	.650	6511.3	.650	6660.6
10	.625	3630.0	.611	3899.0	.611	4029.9
11	.583	920.5	.568	1286.7	.568	1399.2
12	.534	1914.6	.518	1446.6	.518	1353.4
13	.486	4498.6	.468	3937.9	.468	3862.2
14	.452	7208.1	.427	6550.2	.427	6492.9
15	.454	9917.7	.429	9162.5	.429	9123.6
16	.455	12752.7	.430	11895.8	.430	11876.1
17	.578	15514.6	.627	14558.5	.578	14557.6
18	.579	18276.5	.629	17221.3	.579	17239.1

	DECK NO. 1					
19	.735	18489.4	.834	17426.6	.735	17445.9
20	.599	18615.2	.698	17547.8	.599	17568.0
21	.599	18736.9	.698	17665.2	.599	17686.2
22	.599	18832.5	.698	17757.3	.599	17778.9
23	.510	18913.2	.608	17835.1	.617	17857.3
	DECK NO. 2					
24	.335	13631.5	.311	12743.0	.418	12729.3
25	.335	13631.5	.311	12743.0	.418	12729.3
26	.335	13631.5	.311	12743.0	.418	12729.3
27	.335	13631.5	.311	12743.0	.418	12729.3
28	.335	13631.5	.311	12743.0	.418	12729.3
	DECK NO. 3					
29	.332	8986.6	.308	8264.8	.416	8219.5
30	.332	8986.6	.308	8264.8	.416	8219.5
31	.332	8986.6	.308	8264.8	.416	8219.5
32	.332	8986.6	.308	8264.8	.416	8219.5
33	.332	8986.6	.308	8264.8	.416	8219.5
	INNER BOTTOM STRAKES					
34	.629	9342.7	.609	9406.7	.609	9576.4
35	.598	9342.7	.577	9406.7	.577	9576.4
36	.598	9342.7	.577	9406.7	.577	9576.4
37	.598	9342.7	.577	9406.7	.577	9576.4
38	.598	9342.7	.577	9406.7	.577	9576.4
39	.598	9342.7	.577	9406.7	.577	9576.4
40	.598	9342.7	.577	9406.7	.577	9576.4
41	.598	9342.7	.577	9406.7	.577	9576.4

	BENDING	BUCKLING
WT. OF EFFECTIVE MATL	3.97 T/FT.	4.06 T/FT.
MAX. DIFF. IN BENDING STRESS (SIGMA1-LIMIT STRESS)	126.1 PSI	148.3 PSI
MAX. DIFF. IN BUCKLING STRESS (ACTUAL-ALLOWED)	7479.1 PSI	3144.6 PSI
N.A.(ABOVE KEEL)	25.54 FT.	25.75 FT.
SECTION MODULUS		
KEEL	61818.7 FT.SQ.IN.	60880.6 FT.SQ.IN.
DECK	42589.5 FT.SQ.IN.	42535.1 FT.SQ.IN.
LIMITING PRIMARY STRESS	17709.03 PSI	
REQUIRED SECTION MODULUS	43162.97FT.SQ.IN.	

TYPE:

1 TO CYCLE AGAIN WITH THICKNESS FROM BENDING
2 TO CYCLE AGAIN WITH THICKNESS FROM BUCKLING
3 TO STOP WITH THICKNESS FROM BENDING
4 TO STOP WITH THICKNESS FROM BUCKLING

1

RESULTS OF CYCLE NO. 3

	STARTING		BENDING GOVERNS		BUCKLING GOVERNS	
NO.	T	SIGMA1	T	SIGMA1	T	SIGMA1
	SHELL STRAKES					
1	.974	12364.8	.966	12375.5	.966	12426.0
2	.649	12364.8	.641	12375.5	.641	12426.0
3	.649	12364.8	.641	12375.5	.641	12426.0
4	.649	12364.8	.641	12375.5	.641	12426.0
5	.649	12364.8	.641	12375.5	.641	12426.0
6	.649	12326.3	.641	12337.1	.641	12387.6
7	.650	11390.3	.642	11404.6	.642	11453.5
8	.651	9213.0	.642	9235.2	.642	9280.4
9	.650	6511.3	.645	6543.4	.645	6583.9
10	.611	3899.0	.605	3940.7	.605	3976.7
11	.568	1286.7	.562	1337.9	.562	1369.5
12	.518	1446.6	.512	1385.4	.512	1358.5
13	.468	3937.9	.460	3867.5	.460	3844.9
14	.427	6550.2	.415	6470.2	.415	6452.2
15	.429	9162.5	.416	9073.0	.416	9059.4
16	.430	11895.8	.418	11796.3	.418	11787.4
17	.627	14558.5	.638	14449.3	.627	14445.0
18	.629	17221.3	.639	17102.3	.629	17102.5

	DECK NO. 1					
19	.834	17426.6	.855	17306.9	.834	17307.5
20	.698	17547.8	.719	17427.6	.698	17428.5
21	.698	17665.2	.719	17544.6	.698	17545.6
22	.698	17757.3	.719	17636.4	.698	17637.5
23	.608	17835.1	.629	17713.9	.608	17715.2
	DECK NO. 2					
24	.311	12743.0	.298	12640.4	.327	12633.0
25	.311	12743.0	.298	12640.4	.327	12633.0
26	.311	12743.0	.298	12640.4	.327	12633.0
27	.311	12743.0	.298	12640.4	.327	12633.0
28	.311	12743.0	.298	12640.4	.327	12633.0
	DECK NO. 3					
29	.308	8264.8	.296	8178.6	.325	8163.4
30	.308	8264.8	.296	8178.6	.325	8163.4
31	.308	8264.8	.296	8178.6	.325	8163.4
32	.308	8264.8	.296	8178.6	.325	8163.4
33	.308	8264.8	.296	8178.6	.325	8163.4
	INNER BOTTOM STRAKES					
34	.609	9406.7	.602	9428.2	.602	9473.7
35	.577	9406.7	.570	9428.2	.570	9473.7
36	.577	9406.7	.570	9428.2	.570	9473.7
37	.577	9406.7	.570	9428.2	.570	9473.7
38	.577	9406.7	.570	9428.2	.570	9473.7
39	.577	9406.7	.570	9428.2	.570	9473.7
40	.577	9406.7	.570	9428.2	.570	9473.7
41	.577	9406.7	.570	9428.2	.570	9473.7

	BENDING	BUCKLING
WT. OF EFFECTIVE MATL	3.95 T/FT.	3.97 T/FT.
MAX. DIFF. IN BENDING STRESS (SIGMA1-LIMIT STRESS)	4.8 PSI	6.2 PSI
MAX. DIFF. IN BUCKLING STRESS (ACTUAL-ALLOWED)	320.0 PSI	0.0 PSI
N.A.(ABOVE KEEL)	25.66 FT.	25.72 FT.
SECTION MODULUS		
KEEL	61765.3 FT.SQ.IN.	61513.9 FT.SQ.IN.
DECK	42880.2 FT.SQ.IN.	42876.6 FT.SQ.IN.
LIMITING PRIMARY STRESS	17709.03 PSI	
REQUIRED SECTION MODULUS	43162.97FT.SQ.IN.	

TYPE:

1 TO CYCLE AGAIN WITH THICKNESS FROM BENDING
2 TO CYCLE AGAIN WITH THICKNESS FROM BUCKLING
3 TO STOP WITH THICKNESS FROM BENDING
4 TO STOP WITH THICKNESS FROM BUCKLING

4

LONGITUDINAL STIFFENERS

NO.	X COORD.	Y COORD.	SCANTLINGS	SECTION MODULUS

SECTION NO.10, UP TO INNER BOTTOM IS TRANSVERSELY FRAMED

SECTION NO. 11 ,UP TO DECK NO. 3 IS TRANSVERSELY FRAMED

SECTION NO. 12 ,UP TO DECK NO. 2 IS TRANSVERSELY FRAMED

SECTION NO. 13 ,UP TO DECK NO. 1 IS TRANSVERSELY FRAMED

DECK NO.1 IS TRANSVERSELY FRAMED

DECK NO.2 IS TRANSVERSELY FRAMED

DECK NO.3 IS TRANSVERSELY FRAMED

INNER BOTTOM IS TRANSVERSELY FRAMED

SEAMS

NO.	X COORD.	Y COORD.	THICKNESS	PLT. WIDTH
SEAMS ON SHELL				
1	1.97	0.	.97	1.97
2	7.11	0.	.64	5.15
3	12.76	0.	.64	5.65
4	18.15	0.	.64	5.40
5	23.55	0.	.64	5.40
6	28.94	.08	.64	5.40
7	33.65	2.01	.64	5.15
8	36.93	6.51	.64	5.65
9	37.50	12.09	.64	5.40
10	37.50	17.49	.60	5.40
11	37.50	22.88	.56	5.40
12	37.50	28.53	.51	5.65
13	37.50	33.67	.46	5.15
14	37.50	39.07	.42	5.40
15	37.50	44.47	.42	5.40
16	37.50	50.11	.42	5.65
17	37.50	55.61	.63	5.50
18	37.50	61.11	.63	5.50
DECK NO. 1				
19	31.76	61.54	.83	5.75
20	27.82	61.79	.70	3.95
21	23.38	62.03	.70	4.45
22	19.19	62.22	.70	4.20
23	15.00	62.38	.61	4.20

	NO.	X COORD.	Y COORD.	THICKNESS	PLT. WIDTH
DECK NO.2					
	24	37.50	51.86	.33	5.75
	25	27.81	51.86	.33	3.94
	26	23.38	51.86	.33	4.44
	27	19.19	51.86	.33	4.19
	28	15.00	51.86	.33	4.19
DECK NO.3					
	29	31.75	42.61	.32	5.75
	30	27.81	42.61	.32	3.94
	31	23.38	42.61	.32	4.44
	32	19.19	42.61	.32	4.19
	33	15.00	42.61	.32	4.19
INNER BOTTOM					
	34	1.97	6.11	.60	1.97
	35	6.88	6.11	.57	4.91
	36	12.54	6.11	.57	5.66
	37	17.70	6.11	.57	5.16
	38	22.61	6.11	.57	4.91
	39	27.77	6.11	.57	5.16
	40	32.93	6.11	.57	5.16
	41	36.53	6.11	.57	3.60
C.V.K.				.56	6.11

APPENDIX B

Combination Framing System

G E N E R A L   C H A R A C T E R I S T I C S

LBP= 550.00,BREADTH= 75.00,DEPTH= 61.11,DRAFT= 27.50,HT. OF CVK= 6.11

NO. DECKS= 3,NO. BHDS= 0,FR.SP.= 30.00,WEB SPACING= 10.00

LONGITUDINALLY FRAMED EXCEPT AS NOTED BELOW

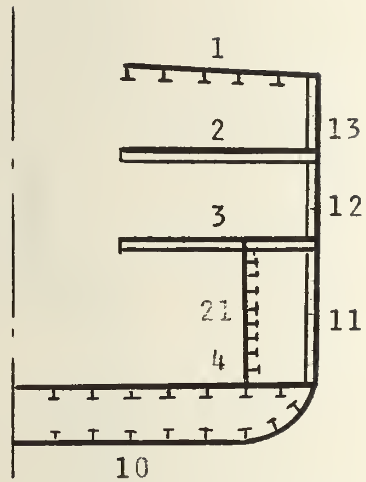
SECTION NO. 2 IS TRANSVERSELY FRAMED

SECTION NO. 3 IS TRANSVERSELY FRAMED

SECTION NO.11 IS TRANSVERSELY FRAMED

SECTION NO.12 IS TRANSVERSELY FRAMED

SECTION NO.13 IS TRANSVERSELY FRAMED



MIDSHIP SECTION

	BENDING	BUCKLING
WT. OF EFFECTIVE MATL	5.12 T/FT.	5.13 T/FT.
MAX. DIFF. IN BENDING STRESS (SIGMA1-LIMIT STRESS)	-374.7 PSI	84.8 PSI
MAX. DIFF. IN BUCKLING STRESS (ACTUAL-ALLOWED)	0. PSI	0. PSI
N.A.(ABOVE KEEL)	23.17 FT.	23.03 FT.
SECTION MODULUS		
KEEL	74619.1 FT.SQ.IN.	73386.8 FT.SQ.IN.
DECK	43836.6 FT.SQ.IN.	42705.3 FT.SQ.IN.
LIMITING PRIMARY STRESS	17709.03 PSI	
REQUIRED SECTION MODULUS	43162.97FT.SQ.IN.	

TYPE:

1 TO CYCLE AGAIN WITH THICKNESS FROM BENDING
2 TO CYCLE AGAIN WITH THICKNESS FROM BUCKLING
3 TO STOP WITH THICKNESS FROM BENDING
4 TO STOP WITH THICKNESS FROM BUCKLING

4

1

LONGITUDINAL STIFFENERS

NO.	X COORD.	Y COORD.	SCANTLINGS	SECTION MODULUS
LONG'LS ON BOTTOM SHELL UP TO INNER BOTTOM,(SPACING=29.5 IN.)				
1	2.46	0.	9.00X 8.75X .751 T	9.670
2	4.91	0.	9.00X 8.75X .751 T	9.670
3	7.37	0.	9.00X 8.75X .751 T	9.670
4	9.83	0.	9.00X 8.75X .751 T	9.670
5	12.28	0.	9.00X 8.75X .751 T	9.670
6	14.74	0.	9.00X 8.75X .751 T	9.670
7	17.20	0.	9.00X 8.75X .751 T	9.670
8	19.66	0.	9.00X 8.75X .751 T	9.670
9	22.11	0.	9.00X 8.75X .751 T	9.670
10	24.57	0.	9.00X 8.75X .751 T	9.670
11	27.03	0.	9.00X 8.75X .751 T	9.670
12	28.75	.16	9.00X 8.75X .751 T	9.670
13	31.09	.90	9.00X 8.75X .751 T	9.670
14	33.16	2.20	9.00X 8.75X .751 T	9.670
15	34.86	3.97	9.00X 8.75X .751 T	9.670

NO.	X COORD.	Y COORD.	SCANTLINGS	SECTION MODULUS

SECTION NO. 11, UP TO DECK NO. 3 IS TRANSVERSELY FRAMED

SECTION NO. 12, UP TO DECK NO. 2 IS TRANSVERSELY FRAMED

SECTION NO. 13, UP TO DECK NO. 1 IS TRANSVERSELY FRAMED

DECK NO. 1 (SPACING = 30.0 IN.)

NO.	X COORD.	Y COORD.	SCANTLINGS	SECTION MODULUS
16	35.00	61.30	4.50X 4.38X .375 T	1.209
17	32.50	61.48	4.50X 4.38X .375 T	1.209
18	30.00	61.65	4.50X 4.38X .375 T	1.209
19	27.50	61.80	4.50X 4.38X .375 T	1.209
20	25.00	61.94	4.50X 4.38X .375 T	1.209
21	22.50	62.07	4.50X 4.38X .375 T	1.209
22	20.00	62.18	4.50X 4.38X .375 T	1.209
23	17.50	62.28	4.50X 4.38X .375 T	1.209
24	15.00	62.37	4.50X 4.38X .375 T	1.209

NO.	X COORD.	Y COORD.	SCANTLINGS	SECTION MODULUS
DECK NO.2 IS TRANSVERSELY FRAMED				
DECK NO.3 IS TRANSVERSELY FRAMED				
INNER BOTTOM,(SPACING=29.5 IN.)				
25	2.46	6.11	8.10X 7.87X .676 T	7.049
26	4.91	6.11	8.10X 7.87X .676 T	7.049
27	7.37	6.11	8.10X 7.87X .676 T	7.049
28	9.83	6.11	8.10X 7.87X .676 T	7.049
29	12.28	6.11	8.10X 7.87X .676 T	7.049
30	14.74	6.11	8.10X 7.87X .676 T	7.049
31	17.20	6.11	8.10X 7.87X .676 T	7.049
32	19.66	6.11	8.10X 7.87X .676 T	7.049
33	22.11	6.11	8.10X 7.87X .676 T	7.049
34	24.57	6.11	8.10X 7.87X .676 T	7.049
35	27.03	6.11	8.10X 7.87X .676 T	7.049
36	29.48	6.11	8.10X 7.87X .676 T	7.049
37	31.94	6.11	8.10X 7.87X .676 T	7.049
38	34.36	6.11	8.10X 7.87X .676 T	7.049
BHD NO.1(SPACING=31.3 IN.)				
25	27.03	8.72	8.55X 8.31X .713 T	8.312
26	27.03	11.33	8.55X 8.31X .713 T	8.312
27	27.03	13.93	8.55X 8.31X .713 T	8.312
28	27.03	16.54	8.55X 8.31X .713 T	8.312
29	27.03	19.15	8.55X 8.31X .713 T	8.312

NO.	X COORD.	Y COORD.	SCANTLINGS	SECTION MODULUS
BHD NO. 1 (CCNT.)				
30	27.03	21.75	8.55X 8.31X .713 T	8.312
31	27.03	24.36	8.55X 8.31X .713 T	8.312
32	27.03	26.97	8.55X 8.31X .713 T	8.312
33	27.03	29.58	8.55X 8.31X .713 T	8.312
34	27.03	32.18	8.55X 8.31X .713 T	8.312
35	27.03	34.79	8.55X 8.31X .713 T	8.312
36	27.03	37.40	8.55X 8.31X .713 T	8.312
37	27.03	40.00	8.55X 8.31X .713 T	8.312

SEAMS

NO.	X COORD.	Y COORD.	THICKNESS	PLT. WIDTH
SEAMS ON SHELL				
1	1.97	0.	.66	1.97
2	7.11	0.	.45	5.15
3	12.76	0.	.47	5.65
4	18.15	0.	.49	5.40
5	23.55	0.	.51	5.40
6	28.[illegible]4	.08	.53	5.40
7	33.65	2.01	.53	5.15
8	36.93	6.51	.52	5.65
9	37.50	11.84	.65	5.40
10	37.50	17.24	.61	5.40
11	37.50	22.63	.56	5.40
12	37.50	28.28	.51	5.65
13	37.50	33.42	.46	5.15
14	37.50	38.82	.42	5.40
15	37.50	44.22	.42	5.40
16	37.50	49.86	.42	5.65
17	37.50	55.36	.60	5.50
18	37.50	61.11	.60	5.75

	NO.	X COORD.	Y COORD.	THICKNESS	PLT. WIDTH
DECK NO.1					
	19	31.76	61.54	.50	5.75
	20	27.82	61.79	.51	3.95
	21	23.38	62.03	.51	4.45
	22	19.19	62.22	.51	4.20
	23	15.00	62.38	.51	4.45
DECK NO.2					
	24	31.75	51.86	.39	5.75
	25	27.56	51.86	.39	4.19
	26	23.38	51.86	.39	4.19
	27	19.19	51.86	.39	4.19
	28	15.00	51.86	.39	4.19
DECK NO.3					
	29	31.75	42.61	.37	5.75
	30	27.56	42.61	.33	4.19
	31	23.38	42.61	.33	4.19
	32	19.19	42.61	.33	4.19
	33	15.00	42.61	.33	4.19

NO.	X COORD.	Y COORD.	THICKNESS	PLT. WIDTH
INNER BOTTOM				
34	1.97	6.11	.48	1.97
35	6.88	6.11	.48	4.91
36	12.54	6.11	.48	5.66
37	17.70	6.11	.48	5.16
38	22.61	6.11	.48	4.91
39	27.77	6.11	.48	5.16
40	32.93	6.11	.48	5.16
41	36.78	6.11	.48	3.85
BHD NO.1				
42	27.03	11.58	.32	5.46
43	27.03	16.79	.32	5.21
44	27.03	22.00	.25	5.21
45	27.03	27.22	.18	5.21
46	27.03	32.43	.25	5.21
47	27.03	37.65	.32	5.21
48	27.03	42.61	.28	4.71
C.V.K.			.57	6.11

APPENDIX C

Combination Framing System

GENERAL CHARACTERISTICS

LBP= 550.00,BREADTH= 75.00,DEPTH= 61.11,DRAFT= 27.50,HT. OF CVK= 6.11

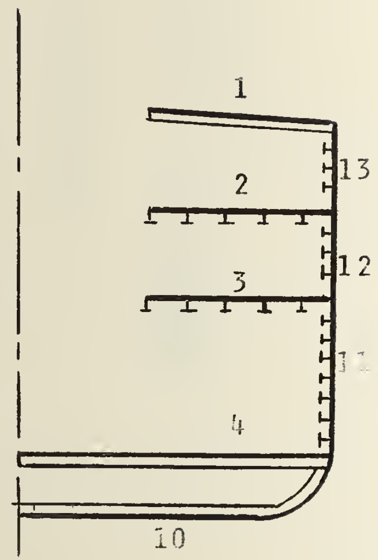
NO. DECKS= 3,NO. BHDS= 0,FR.SP.= 30.00,WEB SPACING= 10.00

LONGITUDINALLY FRAMED EXCEPT AS NOTED BELOW

SECTION NO. 1 IS TRANSVERSELY FRAMED

SECTION NO. 4 IS TRANSVERSELY FRAMED

SECTION NO.10 IS TRANSVERSELY FRAMED



MIDSHIP SECTION

	BENDING	BUCKLING
WT. OF EFFECTIVE MATL	4.17 T/FT.	4.19 T/FT.
MAX. DIFF. IN BENDING STRESS (SIGMA1-LIMIT STRESS)	102.1 PSI	100.7 PSI
MAX. DIFF. IN BUCKLING STRESS (ACTUAL-ALLOWED)	1948.9 PSI	359.2 PSI
N.A.(ABOVE KEEL)	25.76 FT.	25.80 FT.
SECTION MODULUS		
KEEL	61008.7 FT.SQ.IN.	60832.0 FT.SQ.IN.
DECK	42645.3 FT.SQ.IN.	42648.3 FT.SQ.IN.
LIMITING PRIMARY STRESS	17709.03 PSI	
REQUIFED SECTION MODULUS	43162.97FT.SQ.IN.	

TYPE:

1 TO CYCLE AGAIN WITH THICKNESS FROM BENDING
2 TO CYCLE AGAIN WITH THICKNESS FROM BUCKLING
3 TO STOP WITH THICKNESS FROM BENDING
4 TO STOP WITH THICKNESS FROM BUCKLING

4

1

LONGITUDINAL STIFFENERS

NO.	X COORD.	Y COORD.	SCANTLINGS	SECTION MODULUS
SECTION NO.10, UP TO INNER BOTTOM IS TRANSVERSELY FRAMED				
LONG'L ON SIDE SHELL UP TO DECK NO.3(SPACING=29.3 IN.)				
1	36.69	8.46	8.19X 7.96X .683 T	7.287
2	37.50	10.90	8.19X 7.96X .683 T	7.287
3	37.50	13.34	8.19X 7.96X .683 T	7.287
4	37.50	15.78	8.19X 7.96X .683 T	7.287
5	37.50	18.22	8.19X 7.96X .683 T	7.287
6	37.50	20.66	8.19X 7.96X .683 T	7.287
7	37.50	23.09	8.19X 7.96X .683 T	7.287
8	37.50	25.53	8.28X 8.05X .691 T	7.530
9	37.50	27.97	8.28X 8.05X .691 T	7.530
10	37.50	30.41	8.28X 8.05X .691 T	7.530
11	37.50	32.85	8.37X 8.14X .698 T	7.778
12	37.50	35.29	8.46X 8.22X .706 T	8.032
13	37.50	37.73	8.46X 8.22X .706 T	8.032
14	37.50	40.17	8.55X 8.31X .713 T	8.291

NO.	X COORD.	Y COORD.	SCANTLINGS	SECTION MODULUS
LONG'L ON SIDE SHELL UP TO DECK NO.2(SPACING=27.7 IN.)				
15	37.50	44.92	8.55X 8.31X .713 T	8.291
16	37.50	47.24	8.10X 7.87X .676 T	7.049
17	37.50	49.55	8.10X 7.87X .676 T	7.049
LONG'L ON SIDE SHELL UP TO DECK NO.1(SPACING=27.7 IN.)				
18	37.50	54.17	8.01X 7.79X .668 T	6.817
19	37.50	56.49	8.01X 7.79X .668 T	6.817
20	37.50	58.80	8.01X 7.79X .668 T	6.817
DECK NO.1 IS TRANSVERSELY FRAMED				
DECK NO.2(SPACING=30.0 IN.)				
21	35.00	51.86	4.59X 4.46X .383 T	1.283
22	32.50	51.86	4.59X 4.46X .383 T	1.283
23	30.00	51.86	4.59X 4.46X .383 T	1.283
24	27.50	51.86	4.59X 4.46X .383 T	1.283
25	25.00	51.86	4.59X 4.46X .383 T	1.283
26	22.50	51.86	4.59X 4.46X .383 T	1.283
27	20.00	51.86	4.59X 4.46X .383 T	1.283
28	17.50	51.86	4.59X 4.46X .383 T	1.283
29	15.00	51.86	4.59X 4.46X .383 T	1.283

NO.	X COORD.	Y COORD.	SCANTLINGS	SECTION MODULUS
DECK NO.3(SPACING=30.0 IN.)				
30	35.00	42.61	4.14X 4.02X .345 T	.941
31	32.50	42.61	4.14X 4.02X .345 T	.941
32	30.00	42.61	4.14X 4.02X .345 T	.941
33	27.50	42.61	4.14X 4.02X .345 T	.941
34	25.00	42.61	4.14X 4.02X .345 T	.941
35	22.50	42.61	4.14X 4.02X .345 T	.941
36	20.00	42.61	4.14X 4.02X .345 T	.941
37	17.50	42.61	4.14X 4.02X .345 T	.941
38	15.00	42.61	4.14X 4.02X .345 T	.941

INNER BOTTOM IS TRANSVERSELY FRAMED

SEAMS

NO.	X COORD.	Y COORD.	THICKNESS	PLT. WIDTH
SEAMS ON SHELL				
1	1.97	0.	.97	1.97
2	7.11	0.	.65	5.15
3	12.76	0.	.65	5.65
4	18.15	0.	.65	5.40
5	23.55	0.	.65	5.40
6	28.94	.08	.65	5.40
7	33.65	2.01	.65	5.15
8	36.93	6.51	.65	5.65
9	37.50	12.09	.50	5.40
10	37.50	17.49	.44	5.40
11	37.50	22.88	.38	5.40
12	37.50	28.53	.33	5.65
13	37.50	33.67	.30	5.15
14	37.50	39.07	.28	5.40
15	37.50	44.47	.24	5.40
16	37.50	50.11	.21	5.65
17	37.50	55.61	.42	5.50
18	37.50	61.11	.51	5.50

	NO.	X COORD.	Y COORD.	THICKNESS	PLT. WIDTH
DECK NO.1					
	19	31.76	61.54	.64	5.75
	20	27.82	61.79	.59	3.95
	21	23.38	62.03	.59	4.45
	22	19.19	62.22	.59	4.20
	23	15.00	62.38	.51	4.19
DECK NO.2					
	24	31.75	51.86	.35	5.75
	25	27.81	51.86	.35	3.94
	26	23.38	51.86	.35	4.44
	27	19.19	51.86	.35	4.19
	28	15.00	51.86	.35	4.19
DECK NO.3					
	29	31.75	42.61	.30	5.75
	30	27.81	42.61	.30	3.94
	31	23.38	42.61	.30	4.44
	32	19.19	42.61	.30	4.19
	33	15.00	42.61	.30	4.19
INNER BOTTOM					
	34	1.97	6.11	.61	1.97
	35	6.88	6.11	.57	4.91
	36	12.54	6.11	.57	5.66
	37	17.70	6.11	.57	5.16
	38	22.61	6.11	.57	4.91
	39	27.77	6.11	.57	5.16
	40	32.93	6.11	.57	5.16
	41	36.53	6.11	.57	3.60
C.V.K.				.57	6.11

BIBLIOGRAPHY

1. Antoniou, A. C., "An Analysis of the American Bureau of Shipping Rules with Application to the Design of a Longitudinally Framed Tanker", SNAME, New England Section, 1960.

2. Courtsal, D., "An Approach to the Design of the Midsection of Longitudinally Framed Tankers", S.M. Thesis, M.I.T., 1956.

3. D'Arcangelo, A. M., A Guide to Sound Ship Structures, Maritime Press, Baltimore, 1965.

4. Dantzig, G. B., Linear Programming and Extensions, Princeton University Press, Princeton, N. J., 1963.

5. Davis, R. G., "Digital Computer Solutions of Amidship Structural Design Problems", Naval Engineers Thesis, M.I.T., 1960.

6. Design and Construction of Steel Merchant Ships, Edited by P. Arnott, SNAME, 1955.

7. DET NORSKE VERITAS, "Rules for Construction and Classification of Steel Ships", 1962.

8. Evans, J. Harvey, "A Structural Analysis and Design Integration", SNAME Transactions, 1958.

9. Evans, J. Harvey and Khoushy, D., "Optimized Design of Midship Section Structure", SNAME, 1963.

10. Foley, J. L., "Barges in Ocean Service", SNAME, 1965.

11. Hildebrand, F. B., Introduction to Numerical Analysis, 1956.

12. Khoushy, D., "Weight Strength Analysis of Cargo Ships' Structures", Ph.D. Thesis, M.I.T., 1962.

13. "Load Line Regulations", U. S. Coast Guard, 1962.

14. Rawat, P., "A Design Synthesis of the Primary Ship Structure", Unpublished M.I.T. Memo, 1965.

15. Rules for Building and Classing Steel Vessels, American Bureau of Shipping, 1965.

16. Schade, H. A., "Design Curves for Cross-Stiffened Plating under Uniform Bending Load", SNAME Transactions, 1941.

17. St. Denis, M., "On the Structural Design of the Midship Section", D. W. Taylor Model Basin Report, C-555, 1954.

18. Timoshenko, S., Strength of Materials, D. Van Norstrand, 1955.

Unclassified

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Final Report

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Qualified requesters may obtain copies of this report from DDC.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
----	D. W. Taylor Model Basin Carderock, Maryland

13 ABSTRACT

A computer program for the design synthesis of a ship's midship section structure is developed and described. The logic of cycling from a set of arbitrarily selected initial thicknesses, to an optimum closed solution for least weight was originated in earlier work, and has been used as a basic premise in the formulation of this program. Any arrangement of transverse or longitudinal framing systems with all practical combinations of decks and longitudinal bulkheads is now included within the scope of the design.

The current program is formulated under merchant ship criteria as defined by the American Bureau of Shipping. Substitution of Naval standards, or any other, is easily done. Presently, the structural design is restricted to the midsection of a mild steel ship with a simple hull geometry. The program is intended as a framework for the design of any realistic ship composed of any structural material; therefore, every attempt has been made to make the logical design process general enough so that expansion can be made in several directions without extensive revision of either the theory, or the computer program.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Computer Aided Structural Design						

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